

## Omnidirectional Transport Platform

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14. ABSTRACT ( <i>Maximum 200 words</i> ): <p>This report developed under SBIR contract for Topic N99-051. One important element contributing to the effectiveness and efficiency of Navy sea-based aviation is the movement of aircraft components, munitions, and other support materiel around the flight deck, hangar deck, and magazines. On a typical aircraft carrier, this function consumes thousands of labor hours, hundreds of personnel, and hundreds of pieces of support equipment. The Navy has identified materiel transport as an area to reduce the cost of conducting naval operations while increasing the number of combat missions flown by each aircraft. This project began the development of an Omnidirectional Transport Platform (OTP) that features powered, omnidirectional wheels, a remote operator interface, and compatibility with existing lift and materiel transfer equipment. These features will reduce the number of personnel and support equipment, which will reduce the cost of conducting sea-based air operations. The OTP will improve the flow of materiel through the ship and reduce mean aircraft turn around time (TAT), thus increasing the sortie rate. During Phase I, we developed a functional prototype of an omnidirectional platform. This prototype paves the way for a successful Phase II design by demonstrating the core technical components of omnidirectional wheels and control electronics and software.</p>								
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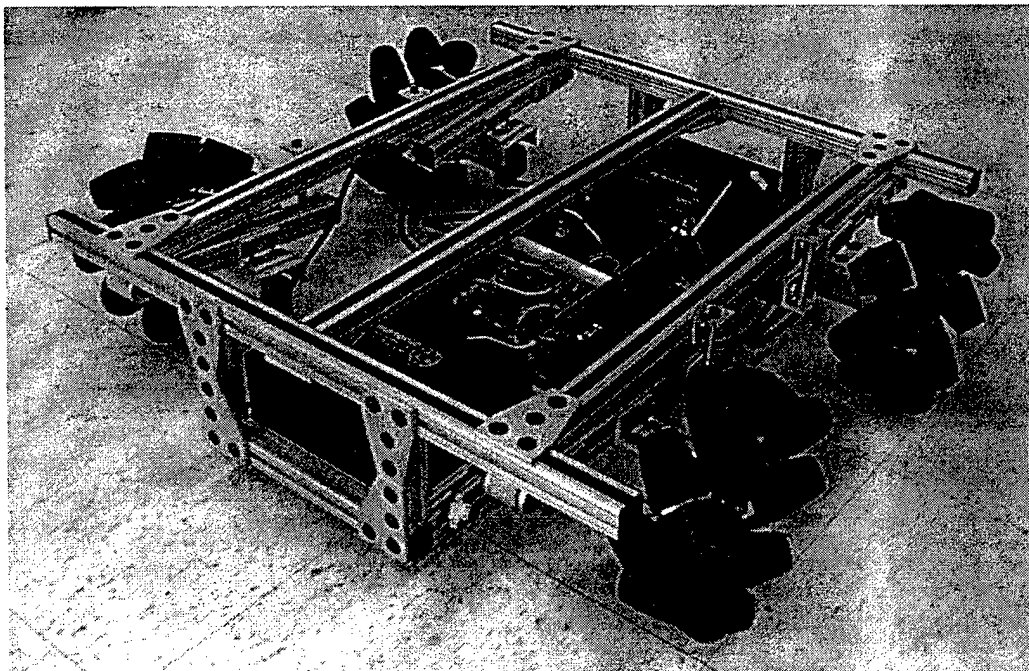
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## **I. INTRODUCTION AND PHASE I PROJECT SUMMARY**

One of the most important elements contributing to the effectiveness and efficiency of Navy and Marine corps sea-based aviation support systems is the movement of aircraft components, munitions, and other aviation support materiel on the flight deck, hangar deck, and throughout the other spaces on the ship. On a typical large deck aircraft carrier, this function consumes many thousands of labor hours, ties up hundreds of personnel, and has hundreds of equipment items dedicated for this purpose. Two important requirements in today's Navy are demanding major changes in the way the Navy operates its sea aircraft: the need to reduce the cost of conducting naval operations and the need to increase the number of combat missions flown by each aircraft. More details of the project background are included in Appendix A.

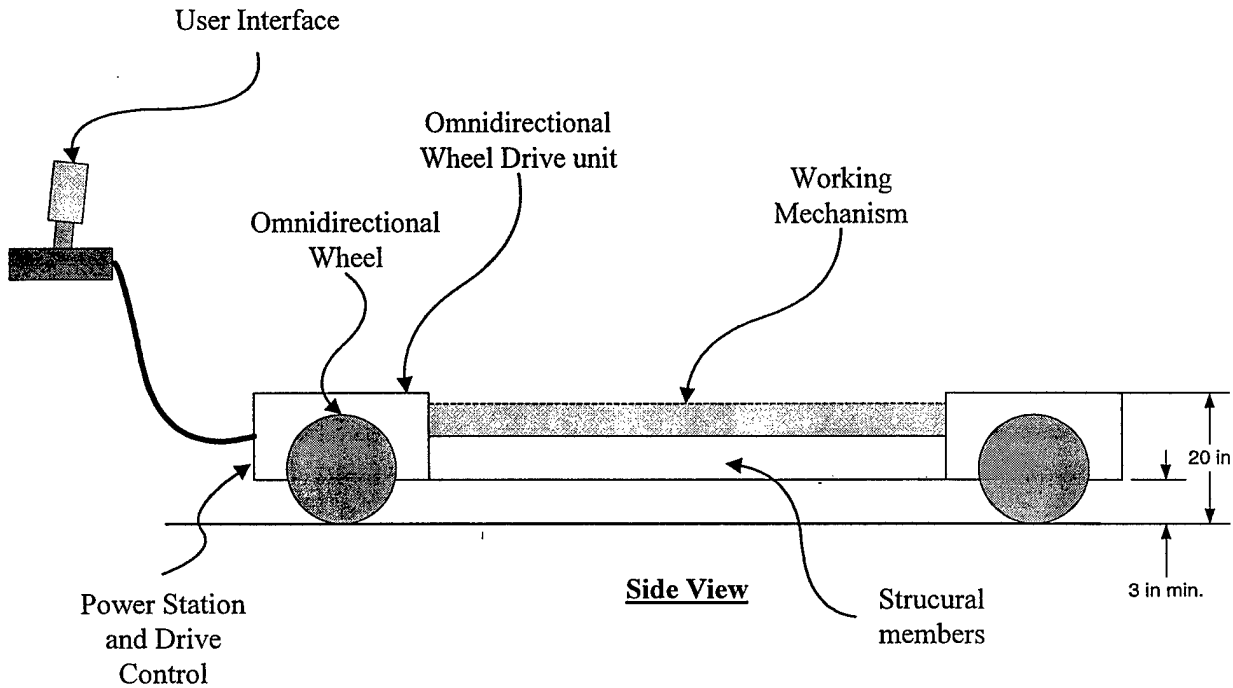
This project began the development of an Omnidirectional Transport Platform (OTP) which addresses the problem of reducing operating costs while increasing the number of combat missions. This platform features powered, omnidirectional wheels, a remote control operator interface, and compatibility with existing lift and materiel transfer equipment such as engine lifts and munitions carriers. These features will reduce the number of personnel and support equipment needed, which will reduce the cost of conducting sea-based air operations. The second benefit of the OTP will be to improve the flow of materiel through the ship and reduce mean aircraft turn around time (TAT), thus increasing the sortie rate.

During the Phase I research, we focused on the omnidirectional wheel technology and control electronics and software. Cybernet has a strong background in the development of multi-axis robots, coordinated motor control, human-machine interface, and control electronics. This research effort culminated in a functional prototype, as shown in Figure 1.



**Figure 1: Phase I Prototype System**

A schematic of the Phase II Omnidirectional Transport Platform is shown in Figure 2. This schematic shows the major components of the OTP. The core technology is the omnidirectional wheel drive unit. Three or four of these omnidirectional drive units will be assembled by means of structural elements to make the OTP. The OTP needs an on-board power station and drive control software to coordinate the motion of the omnidirectional wheel units. This control software will respond to the user interface, shown in Figure 2 as a joystick. The working mechanism is the payload-specific hardware which will be mounted on the platform to configure the OTP for a specific purpose, such as engine replacement or weapons handling.



**Figure 2: Omnidirectional Transport Platform**

## **II. PHASE I WORK**

The Phase I research was accomplished by the following steps:

1. Identify shipboard working conditions and develop platform performance criteria.
2. Explore omnidirectional wheel technology.
3. Select omnidirectional wheel concept for further study.
4. Design omnidirectional wheel unit and prototype platform.
5. Perform power system trade studies.
6. Design concepts for Phase II Omnidirectional Transport Platform.
7. Construct a scale prototype of an omnidirectional platform.

### A. Performance Criteria

A majority of the performance criteria were identified as part of the "System Innovation and Development Guidance Document" (SIDGD). Samples of the performance criteria are noted in Figure 3. We also went aboard the aircraft carrier USS Harry S. Truman (CVN 75) to observe the material transport paths on the carrier, see the working conditions, and speak with the personnel involved with materiel transport.

Parameter	Units	Specification	Notes
Capacity	lbs	6000 12000	4000 min for horseshoe config 9500 min for box config
Weight	lbs		
Length	in		
Width	in		
Height	in	20	24 max
Ground Clearance	in	3	hangar bay fire door sill
Speed - Max	mph	5	
Speed - Typical	mph	3	
Safety Factor (design)		3	designed against yield
Safety Factor (tested)		2	designed against yield

**Figure 3: Major System Parameters, As Described In The Systems Innovation and Development Guidance Document (SIDGD)**

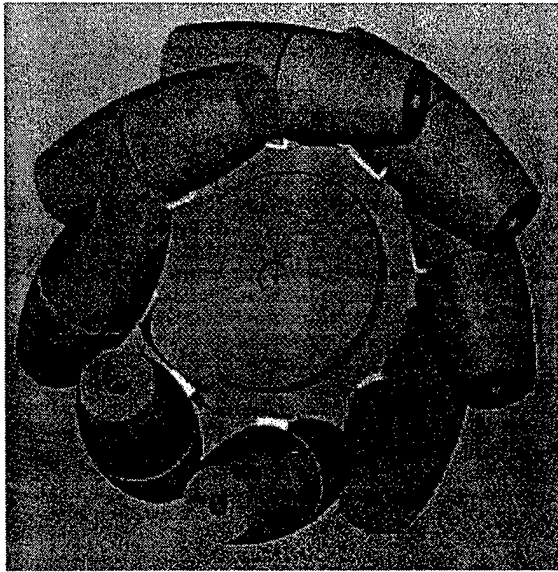
### B. Omnidirectional Wheel Technology

Omnidirectional wheel technology is the fundamental technology for the OTP. Research in this area was the focus of the Phase I activity, culminating in a prototype of an omnidirectional platform. These omnidirectional wheels allow the platform to be driven in any direction from any orientation. This provides significant improvement in mobility around objects and decreases the time necessary to correctly position the payload during aircraft servicing or weapons loading. This section presents an overview of four classes of omnidirectional wheels: Mecanum wheel, steerable driving wheels, universal wheel, and orthogonal-wheels. A complete discussion of the wheel technologies can be found in Appendix B.

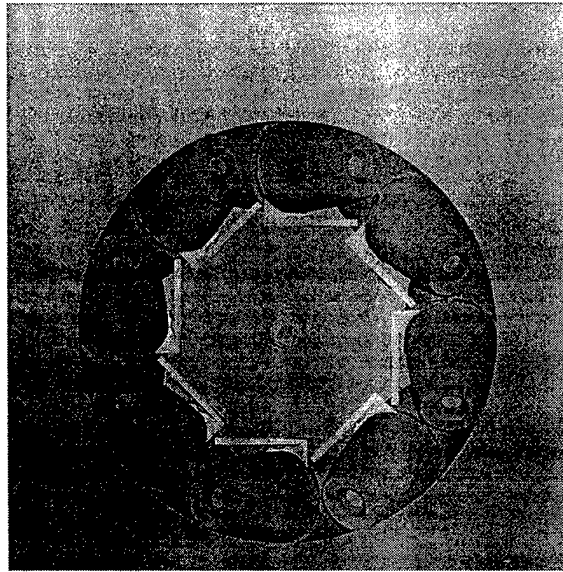
We selected the Mecanum wheel as the omnidirectional wheel technology for this project. We did not choose the steerable driving wheel because of tire wear due to scrubbing. We did not choose the orthogonal wheel concept because of poor performance of this technology during obstacle traversal. These wheels work best on flat, smooth surfaces. We did not select the universal wheel because of the sharp transitions between different idlers, which would result in a periodic jarring and vibration to the carried load. The Mecanum wheel provides a smoother ride than the universal wheel, reduces tire wear as compared to the steerable driving wheel, and has better obstacle traversal performance than the orthogonal wheel concept.

This class of wheel is called the Mecanum wheel or the Ilon wheel. Like the universal wheel, the Mecanum wheel has passive rollers mounted on the rim of the drive wheel. The universal wheel has the passive rollers mounted 90 degrees to the axis of rotation of the drive wheel. The Mecanum wheel has the rollers mounted at an angle of 45 degrees, as seen in Figure 4. This

allows the rollers to be spaced closer together so that the wheel has an unbroken round profile, as shown in Figure 5. This allows a smoother transition from one roller to the next, making the motion less jarring for the payload.



**Figure 4: Mecanum Wheel**



**Figure 5: Mecanum Wheel, Side View**

The shape of the Mecanum wheel can be constructed by the following process<sup>1</sup>:

1. Choose a roller axis.
2. Pick any point on this axis. Varying this point generates the shape of the entire roller.
3. Pass a perpendicular line from the wheel axis through that point, extending to the cylinder which defines the nominal wheel outer diameter.
4. Since this point on the cylinder surface must also lie on the roller surface, transform this point into the roller coordinate system (at the location  $x_1, y_1, z_1$ ).
5. Calculate the distance from that point to the roller axis (distance =  $\sqrt{x_1^2 + y_1^2}$ ). This is the roller radius at  $z_1$ .
6. Return to step 2, choosing a new point.

---

<sup>1</sup> Lapin, Brett, Stephen Dickerson, and Wiley Holcombe. Omnidirectional Vehicle Survey and Analysis. Georgia Institute of Technology, February 3, 1990.



The curve defining the roller can be found through a parametric equation in terms of  $t$ , which will vary from 0 to the maximum roller length.

Known Dimensions:

$$R = 1/2 * \text{wheel\_diameter}$$

$$b = 1/2 * \text{idler\_roller\_diameter}$$

$$e = \text{attack\_angle\_of\_idler\_roller}$$

$$\text{max\_roller\_length} = 1 / \sin(e) * \sqrt{b * (2 * R - b)}$$

$$0 \leq t \leq \text{max\_roller\_length}$$

$$c = R / \sqrt{(R - b)^2 + t^2 * \sin^2(e)}$$

$$x_1 = (c - 1) * t * \sin(e) * \cos(e)$$

$$y_1 = (c - 1) * (R - b)$$

$$z_1 = c * t * \sin^2(e) + t * \cos^2(e)$$

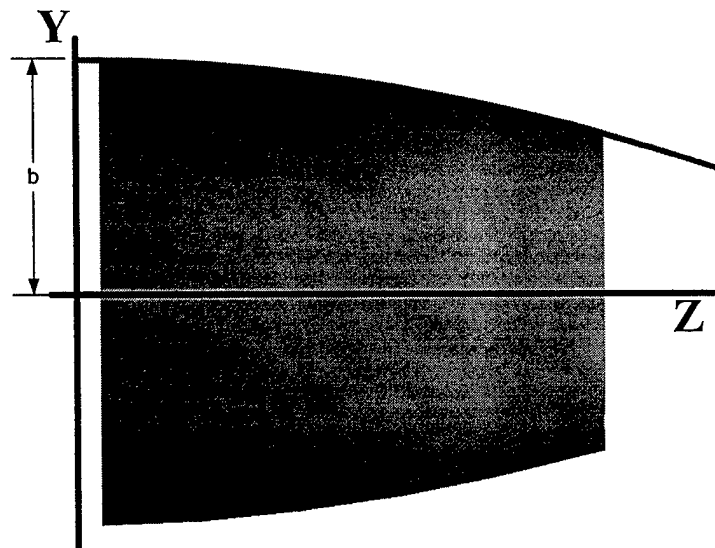
$$\text{local\_radius} = \sqrt{x_1^2 + y_1^2}$$

In the roller coordinate system:

$$x=0$$

$$y=\text{local\_radius}$$

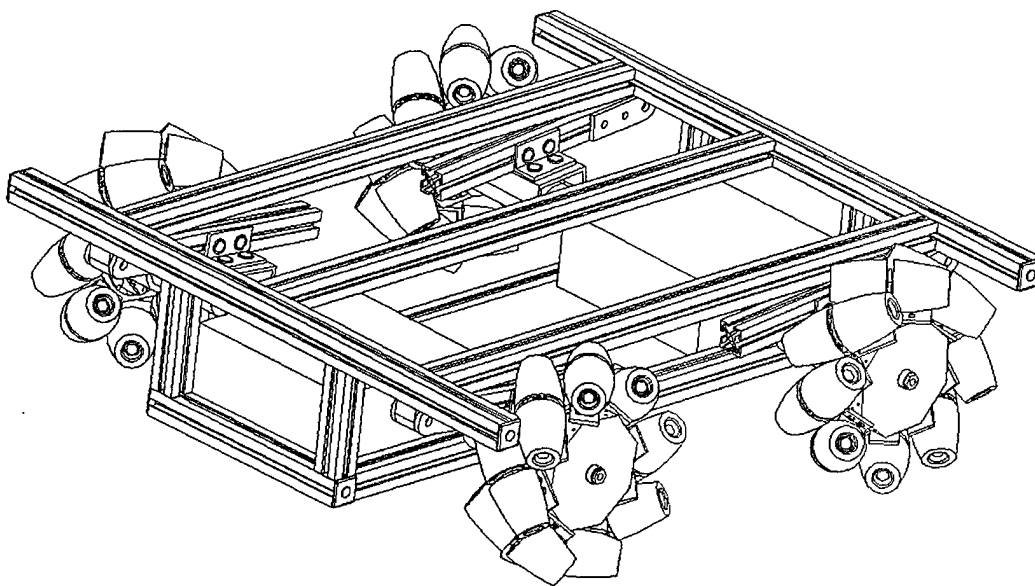
$$z=z_1$$



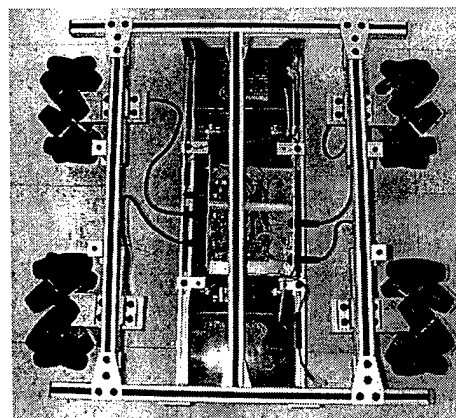
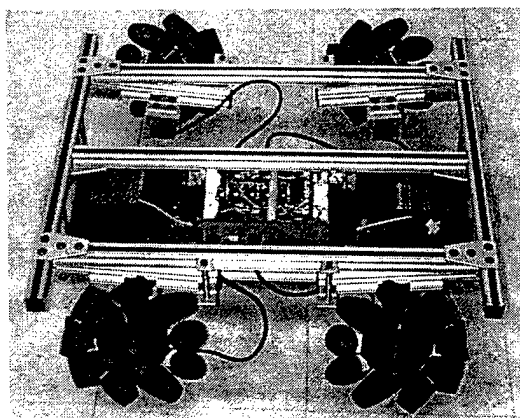
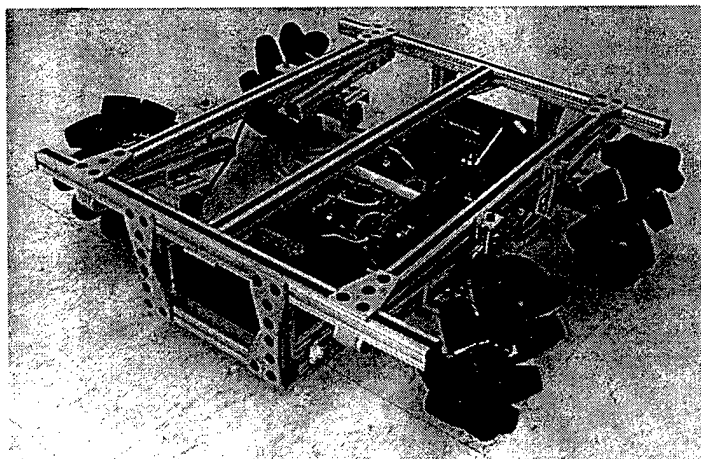
**Figure 6: Equations of Idler Roller Profile**

### C. Prototype

The Phase I prototype demonstrates two fundamental concepts to the success of the Phase II project: omnidirectional wheel design and synchronized motor control. Figure 7 shows a CAD model of the scale prototype. The chassis consists of 1" square modular T-slotted aluminum extrusions. These extrusions offer an alternative to welded frames by utilizing standard parts, fasteners, and joining plates which offer flexibility and ease of assembly. The extrusions are easily assembled with screws, T-slot nuts, and pre-cut joining plates. The 4 Mecanum wheel assemblies are mounted to the chassis to form a trailing arm suspension. The pivots are located at the front and rear of the chassis. The suspension springs are located close to the midline. Each wheel unit is composed of the same modular components. The idler rollers spin freely on plastic bearings which ride on a shoulder bolt for an axle. The shoulder bolts and idler rollers are mounted to an L bracket, which is, in turn, fastened the hub at a 45 degree angle. The hub is directly mounted to the output shaft of a DC gearmotor by means of a keyless bushing. The gearmotor is housed in an aluminum channel for support. This aluminum channel is mounted to the arm of the suspension assembly by two L brackets.



**Figure 7: CAD Model of Scale Prototype**



**Figure 8: Photographs of Phase I Prototype**

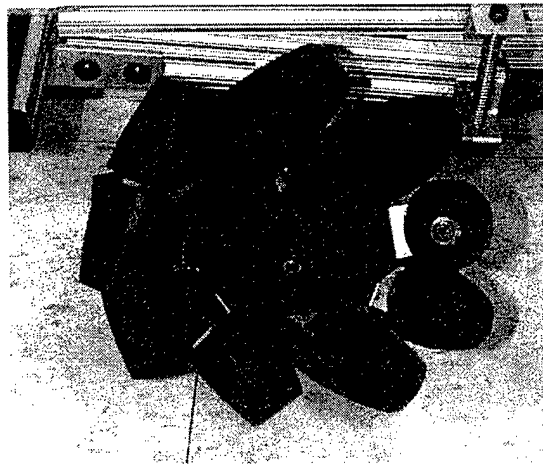
The scale prototype was designed based on the following design parameters:

Dimensions		Weight Calcs	Wt(lb)	Qty
Wheel Diameter	8 in	Wheel	2	4
Length	26 in	Motor and Gearhead	2	4
Width	24 in	Battery	3.5	2
Height	8 in	Frame	8	1
Ground Clearance	3 in	Electronics	0.5	1
		Vehicle Weight	31.5 lb	

Design Parameters			
Payload	20 lb		
Design Safety Factor	1.5		
Drive Train Friction	5% of weight		
Ramp Incline	8 deg		
Speed on max slope	3 mph	52.8 in/s	
Max Speed	5 mph	88 in/s	

### 1. *Omnidirectional Wheel*

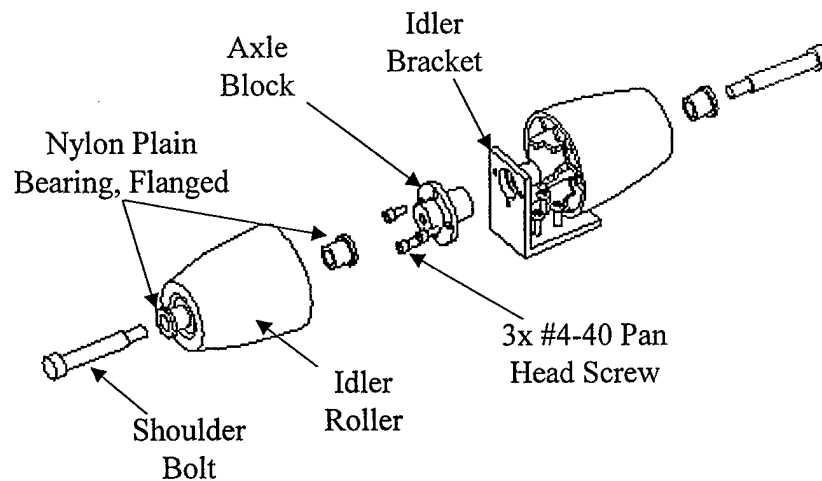
The prototype utilized a Mecanum wheel with 8 idlers. The outer diameter of the wheel was 8 inches, with a nominal idler diameter of 1.75 inches.



**Figure 9: Prototype Omnidirectional Wheel**

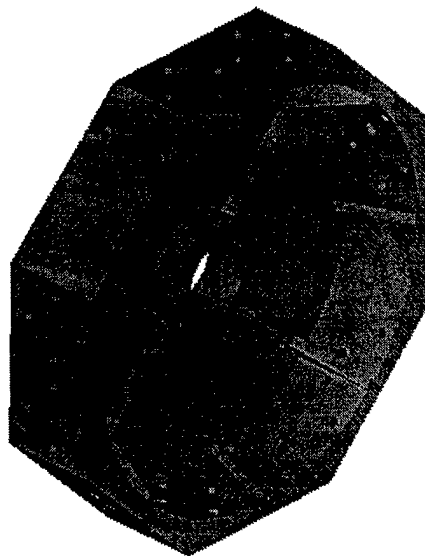
Once the idler shape is determined using the equations from the previous section, the curve is revolved around the idler axis. The idler rollers are made from ABS plastic with walls .120 inches thick. The outer wall was sprayed with 2 coats of rubber to increase traction. Since the roller is mostly hollow, there are 6 internal ribs which strengthen the outer wall and the bearing tube. For the Phase I prototype, the idler rollers were produced on Cybernet's in-house rapid prototype machine. Two nylon flanged plain bearings are pressed into each end of the idler roller, allowing the roller to spin freely about its axle. The idler roller uses 1/4" diameter shoulder bolt as its axle. The shoulder bolts are threaded into the axle block, which in turn is fastened to

the idler bracket. The idler assembly is attached to the hub by 4 screws through the idler bracket. An exploded view of the idler assembly is shown in Figure 10.



**Figure 10: Idler Roller Assembly, Exploded**

To simplify the manufacturing of the Mecanum wheel, we separated the idler mounting bracket from the wheel hub. This allowed us to produce the idler bracket from a standard aluminum angle extrusion. This design was important because the idler bracket needed to be made from aluminum, not ABS, to withstand the bending loads without being made too thick to require a large gap between the two halves of the idler roller. We utilized our in-house rapid prototype (RP) machine to produce the hub out of ABS. By printing the hub in our RP, we eliminated the need for a complicated, and therefore expensive, machining operation. The hub, shown in Figure 11, has 8 sides each with 2 sets of hole patterns set at a 45 degree angle to the hub's rotation axis. These two hole patterns allow us to construct both orientations of the Mecanum wheel out of the same set of parts. The two orientations necessary are: 1) the idler axis at +45 degrees relative to the hub axis, and 2) the idler axis set at -45 degrees.



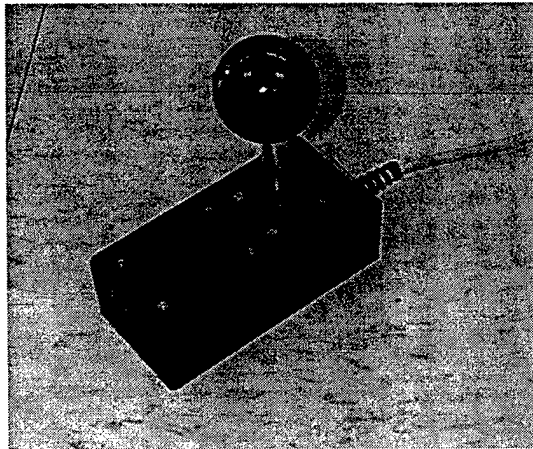
**Figure 11: Hub**

## 2. *Chassis*

The chassis consists of 1" square modular T-slotted aluminum extrusions. These extrusions offer an alternative to welded frames by utilizing standard parts, fasteners, and joining plates which offer flexibility and ease of assembly. The extrusions are easily assembled with screws, T-slot nuts, and pre-cut joining plates. The wheel assemblies are mounted to the chassis to form a trailing arm suspension. The pivots are located at the front and rear of the chassis. The suspension springs are located close to the midline.

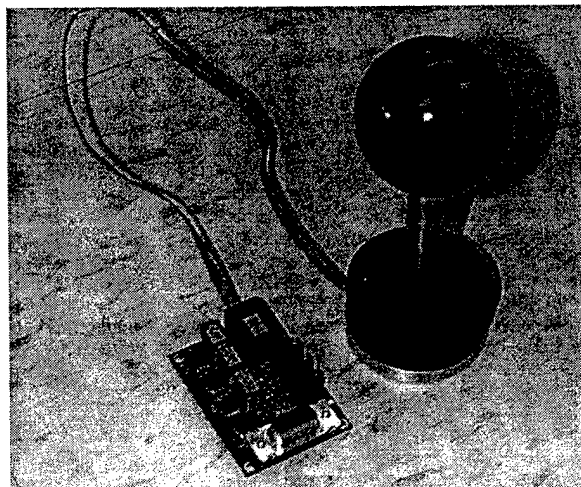
## 3. *User Interface*

The platform is controlled by a tethered joystick, as shown in Figure 12. A non-compliant joystick measures force and commands proportional direction and speed. There is a deadman switch which the user must hold to operate the platform. Releasing this button causes the platform to stop moving and hold that position. Rotation is controlled by a momentary push button switch. When the button is pressed, the right-left motion of the joystick is interpreted as clockwise or counter-clockwise motion about the center of the platform. The front-back motion still controls forward-backward motion. When no force is applied, the unit brakes itself, causing the platform to stop.



**Figure 12: Joystick For Platform Control**

The joystick used by Cybernet in the project is the DX-200 series from Bokam Engineering ([www.bokam.com](http://www.bokam.com)). The DX Series of sensors features a robust all metal, non compliant, palm-activated, motion control force sensitive system that can be used to precisely control heavy industrial and or medical equipment. The DX series addresses the needs of long life, high reliability, motion control applications. The system features sensors with 2 axes of motion control with integrated analog signal processing electronics in one reliable package.



**Figure 13: Force Sensor and Signal Processing Electronics**

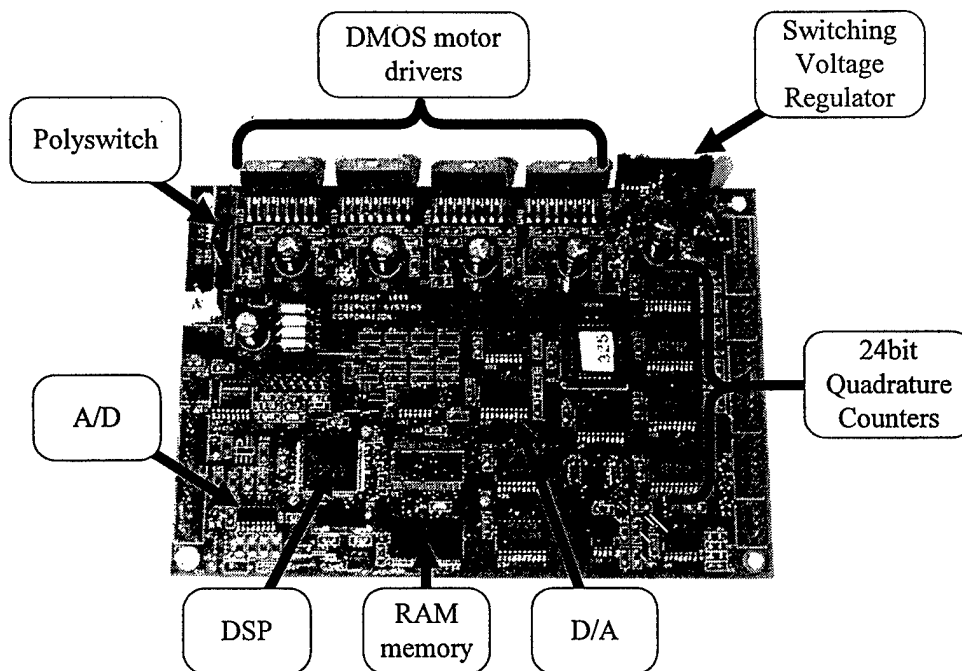
#### *4. Electrical System*

The prototype unit is powered by a 24 volt battery bank which can supply 4 Amp-H of service.

#### **D. Control System**

##### *1. Electrical Hardware*

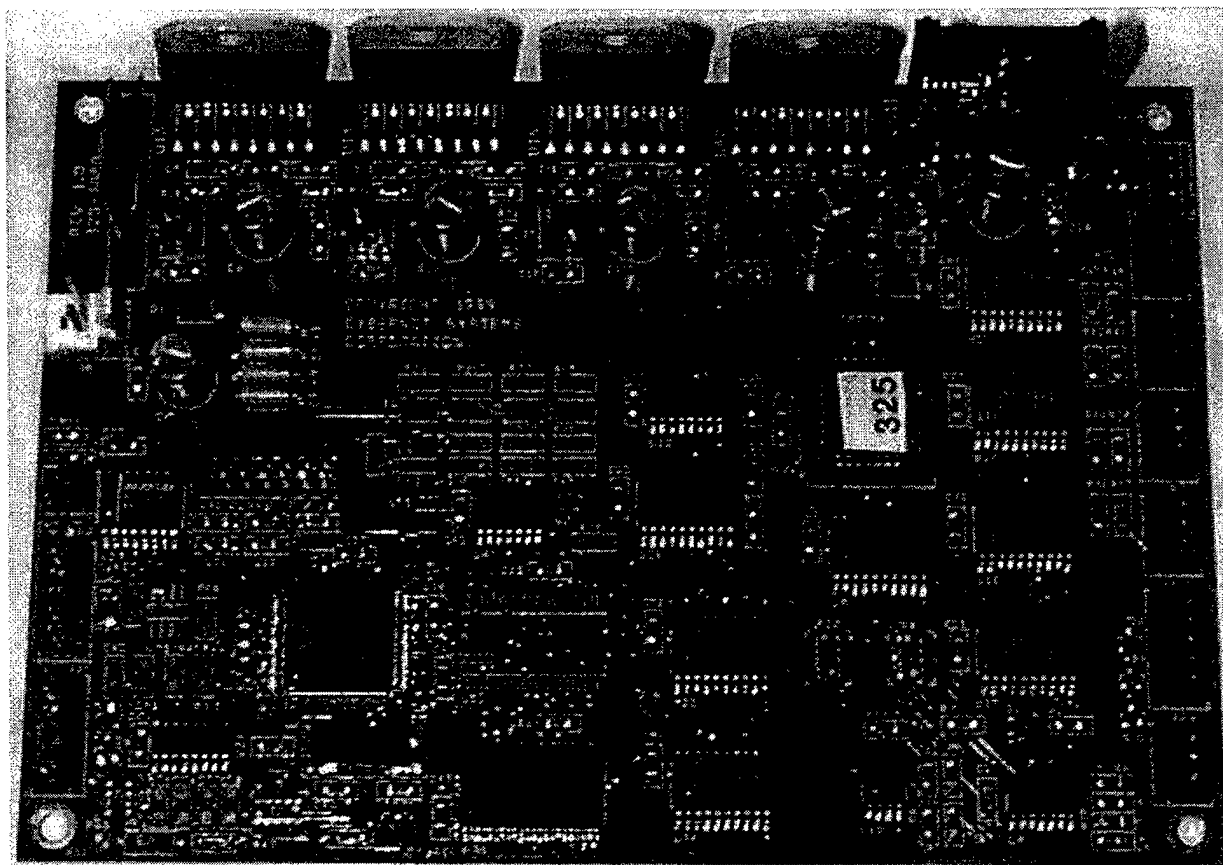
The Omnidirectional Transport Platform (OTP) control unit contains a 4 axis motion controller that takes input from a force sensing joystick. The core of the motion controller system is a TMS320 series digital signal processor (DSP) with internal FLASH memory. The DSP can execute 20 million instructions per second (MIPS). FLASH memory is non-volatile, meaning that it retains its contents even when the power is off. The control code is stored in this memory. The DSP is programmed in C. The rest of the motion controller is made up of a quad 10 bit A/D (analog to digital) converter, four 24 bit quadrature counters, a quad 8 bit D/A (digital to analog) converter, four DMOS motor drives, switching voltage regulator, and miscellaneous glue logic. The DSP operating at 20 MIPS runs a low level PID loop at 1024Hz, taking higher level velocity commands derived from the joystick input to produce coordinated vehicle movement.



**Figure 14: Major Components of the Control Circuit**

The DMOS motor drivers are integrated full-bridge power amplifiers, with internal current sensing, current control, thermal shutdown, over current shutdown, and undervoltage lockout. The quadrature counters have internal 24 bit counters and latches and can operate at speeds up to 20MHz. The quadrature counters supply motor position to the DSP which calculates current motor torques based on the servo control and the joystick inputs. The joystick outputs an analog signal proportional to the force applied. These signals are read by two channels of the A/D converter. The quad D/A convert is used to supply the torque commands to the motor drivers. Multiple digital I/O pins are used to read the dead man button and mode selection. Optional optical deadman sensors are also supported. The OTP control unit can operate from a single unregulated supply ranging from 13.8V to 30VDC. A PolySwitch self resetting fuse and Transient Voltage Suppressor (TVS) provide over current and over voltage protection.

A mode selection button on the control joystick allows the vehicle to be translated in any direction, or to be rotated and translated fore and aft only. The later mode allows rotation about the center of the vehicle and conventional steering while translating fore and aft.



**Figure 15: Control Circuit Board**

## 2. *Software Control*

The software running on the DSP is a customized OTP coordinated control system integrated into Cybernet's Intelligent Motor Controller (IMC) - Serial Communications Protocol (SCP). The SCP is a versatile proprietary protocol for embedded motion control. The protocol dynamically supports multiple devices of different configurations on a single serial chain. This protocol was developed to be highly efficient and expandable to support future devices and functions. The SCP has been used in a variety of Cybernet Commercial products ranging from Force Feedback devices to Data Collection devices.

The OTP coordinated control system uses a position-based velocity control to drive each of the four wheels. Each new position is calculated based on a velocity command derived from the joystick input. This method of control keeps each wheel at its proper position at any given time period. The wheel velocities are calculated based on the joystick input by the following equations:



where:

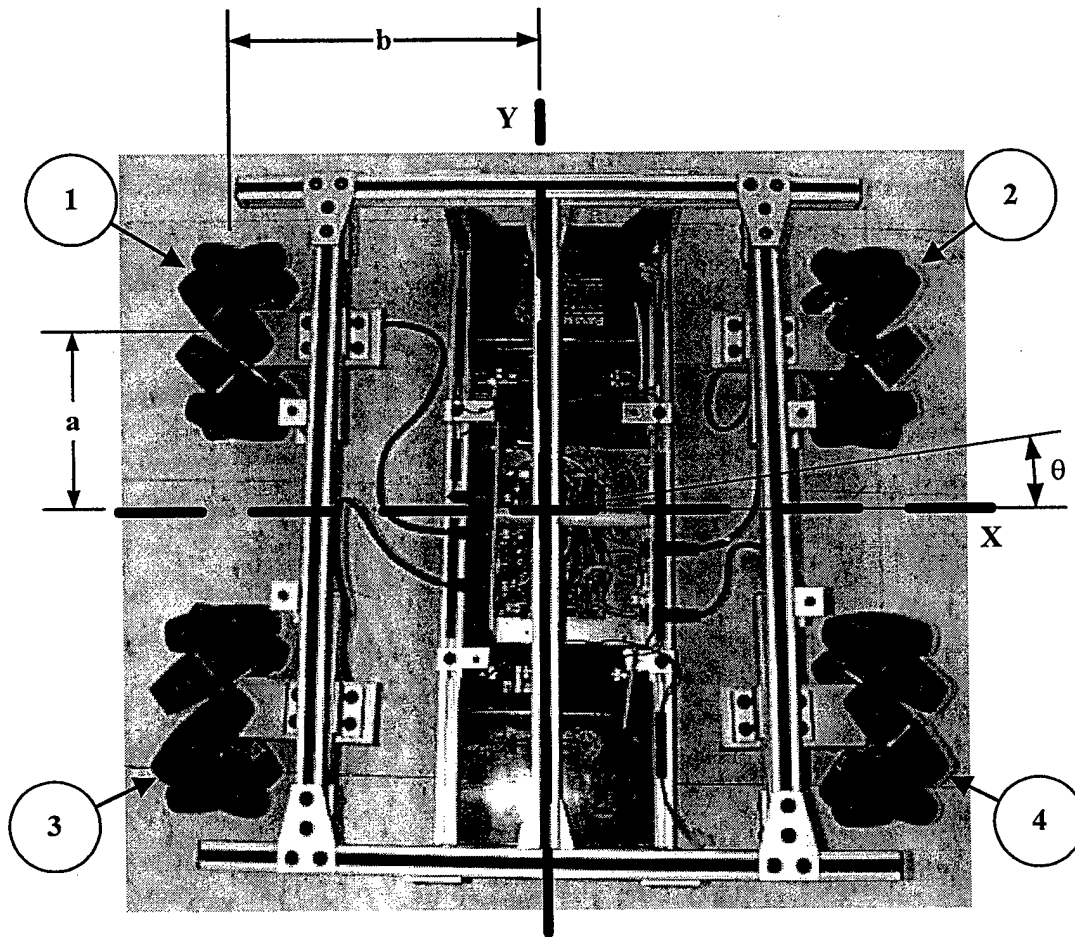
$w$  rotation speed of the wheel  
 ( $w_1$  is the rotation speed of wheel 1)  
 $R$  outer radius of the omnidirectional wheel  
 $V_x$  commanded X velocity of the platform  
 $V_y$  commanded Y velocity of the platform  
 $\theta'$  counterclockwise rotation of the platform  
 $a$  distance (Y) from axle of wheel to origin  
 $b$  distance (X) from wheel center to origin

$$w_1 = [V_y + V_x - (a + b) \cdot \theta'] / R$$

$$w_2 = [V_y - V_x + (a + b) \cdot \theta'] / R$$

$$w_3 = [V_y - V_x - (a + b) \cdot \theta'] / R$$

$$w_4 = [V_y + V_x + (a + b) \cdot \theta'] / R$$



**Figure 16: Dimension Scheme for Control Equations**

The control system for the prototype assumes no spinning or stalled wheel conditions. More advanced control algorithms would be necessary for safety in a full scale vehicle. In order to keep orientation and direction of movement as commanded, each of the wheels must move at the proper rate. If any of the wheels slip or are stalled, the vehicle will turn or move in a different direction. The control system would need to monitor all wheels simultaneously to keep each of

the wheels coordinated to within a certain tolerance. If a wheel or set of wheels begins to spin or are stalled, the other wheels need to adjust accordingly. For transitional movement, because each wheel rotates together with its diagonal counterpart, it is possible to detect a slipping wheel and adjust for the slippage. In most cases end result would be traction control. Any slippage of pair diagonal wheels in transitional movement other than fore and aft cannot be detected. A stalled wheel condition can always be detected. Appropriate actions to take for a stalled wheel condition depend on the cause of the stall (vehicle over loading, obstacle, mechanical breakdown). In most cases a stalled wheel condition would constitute a fault condition and all motion would stop.

### **III. FUTURE WORK**

The Phase I work has lead us to the trailhead for two design paths. The first path is the development of a new platform, based on omnidirectional wheels. The second path would develop upgrade kits for existing transport skids to add the powered omnidirectional functionality. We have decided to pursue the first path during Phase II research. This platform has been named the OTP, Omnidirectional Transport Platform. This new platform will come in 3 sizes, corresponding to the size of the equipment it is designed to replace. This family of omnidirectional skids will be sized to carry the loads currently carried by the MHU-191, ETU 110/E and the model 4000. These 3 skids represent the range of loads moved on board aircraft carriers: from light munitions to aircraft engines. Each platform will consist of the same basic subsystems: chassis, omnidirectional unit, power supply, and control unit. The difference will be in the load ratings of the components.

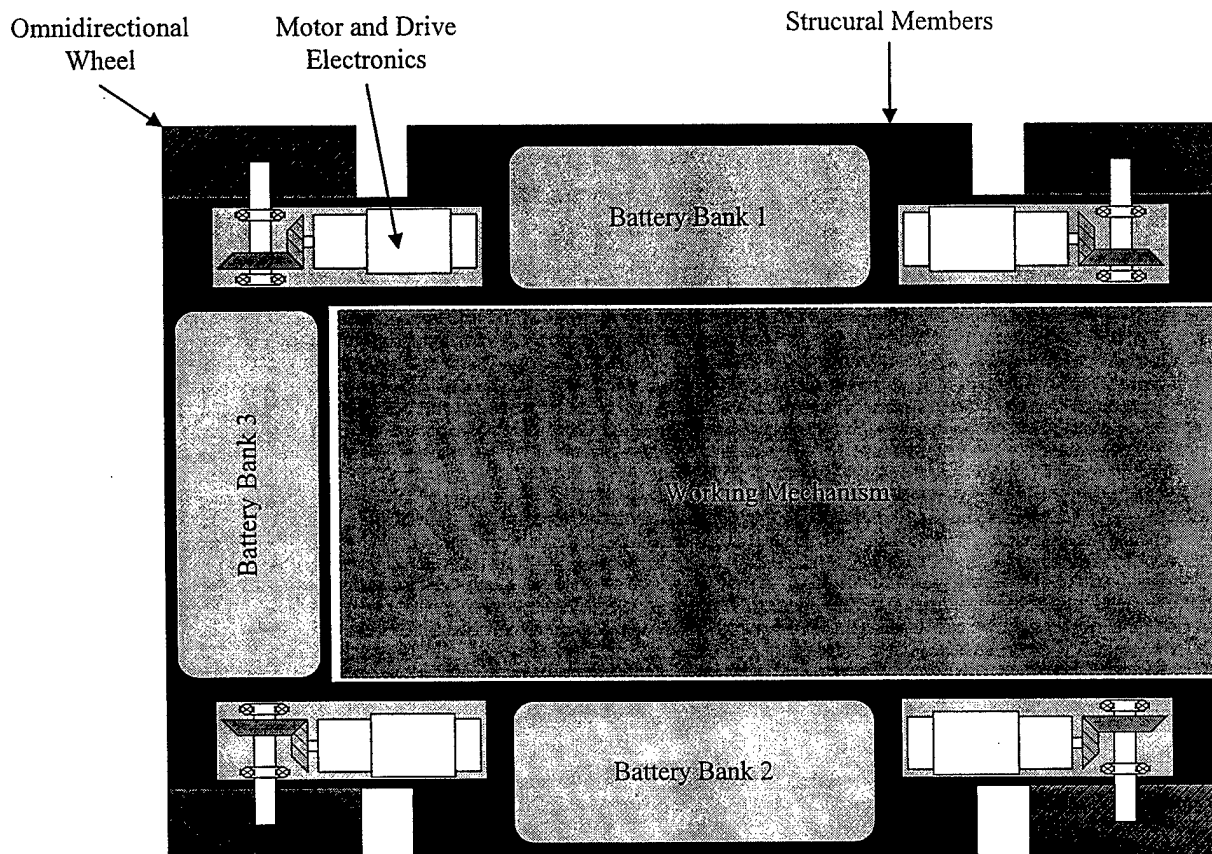
The second path, which we have decided not to pursue, would be to design upgrade kits for existing transport skids to add the powered omnidirectional functionality. One example of an upgrade kit would be powered omnidirectional wheels to replace the casters used on the ETU 110/E. When installing/removing aircraft engines, the skid is towed into an approximate position using conventional wheels. To align the skid correctly, the conventional wheels are raised off the ground and the skid rests on casters. The crew can then push the skid into the exact alignment. This upgrade kit would replace the caster wheels with powered omnidirectional wheels. This would allow the crew to steer the device into exact position. The omni wheels would also eliminate the need for planar (X-Y) adjustments in the engine rail mount.

These kits would be a modular upgrade of the caster assembly, allowing for simple replacement and/or removal. This development path would allow us to focus on the new functionality (omnidirectional wheel) without having to redesign the entire chassis, mounting points, and tow arrangement of the skids. This design path also would provide a lower upgrade cost to existing ships in the fleet.

#### **A. System Design - Omnidirectional Transport Platform (OTP)**

The Omnidirectional Transport Platform (OTP) is a new transport trailer which utilizes omnidirectional wheels. This new platform will come in 3 sizes, corresponding to the size of the equipment it is designed to replace. This family of omnidirectional skids will be sized to carry the loads currently carried by the MHU-191, ETU 110/E, and the model 4000A engine removal and positioning trailer. Each platform will consist of the same basic subsystems: chassis, omnidirectional unit, power supply, and control unit. The difference will be in the load ratings of

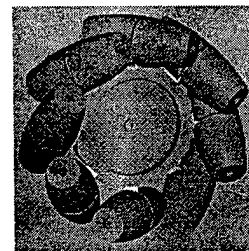
the components. Figure 17 shows a layout of the Phase II system in the horseshoe configuration. The chassis consists of structural members, which are drawn in black in the diagram. The omnidirectional unit is an integrated assembly of the omnidirectional wheel, motor, and drive electronics. The motor will have a right angle gearbox. The power supply consists of three banks of batteries, as shown in the diagram. Three separate battery packs allow the power supply to be distributed around the outside of the device, staying clear of the working mechanism. The control unit is not shown in Figure 17, but will be a joystick mounted to the chassis. These components are described more fully in the following paragraphs.



**Figure 17: Phase II Omnidirectional Transport Platform, Horseshoe Configuration**

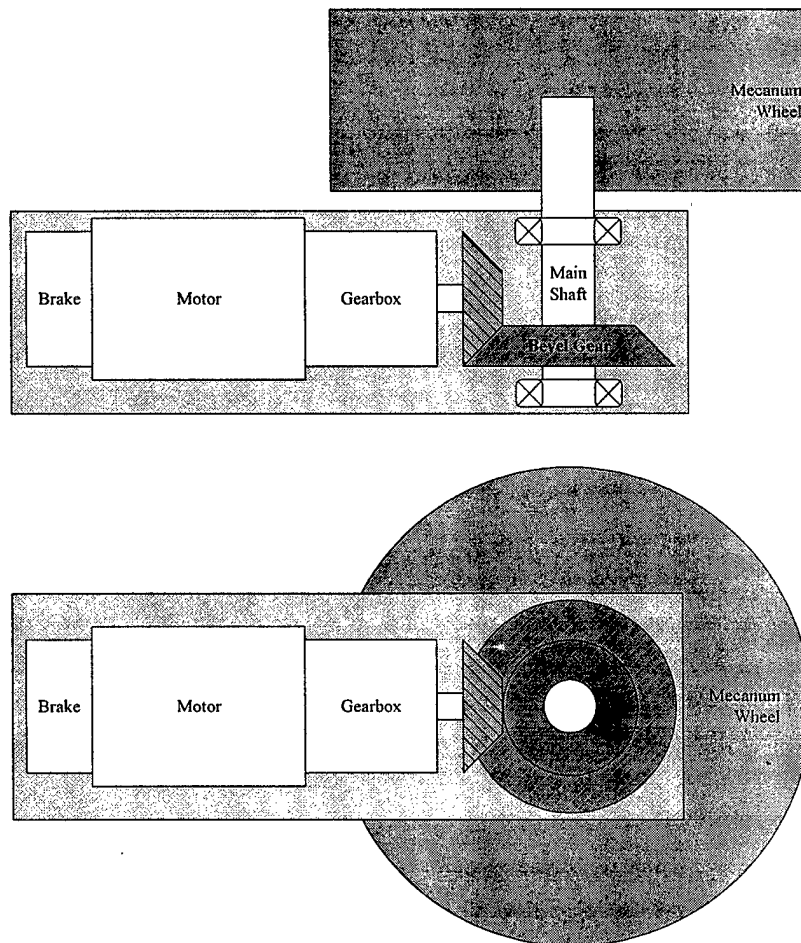
The heart of the device is the omnidirectional wheel. The OTP will use the Mecanum wheel, shown in Figure 18. This is the wheel that was used on the Phase I prototype. The wheel will be designed to satisfy the large load requirements of the Phase II system. The rollers will be made from a metal core with a rubber coating. This rubber will be chosen based on wear characteristics. This is important since the non-skid deck of the aircraft carrier is particularly abrasive.

The omnidirectional wheel unit will be designed to minimize the volume occupied by the drivetrain. This allows the most room inside the frame for the working



**Figure 18: Mecanum Wheel**

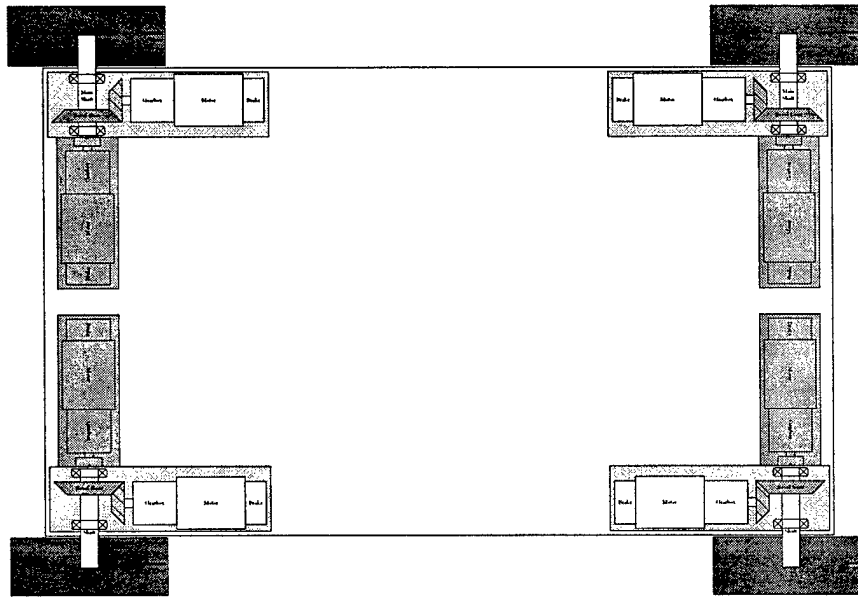
mechanism. Figure 19 shows a top view and side view of the drivetrain. The Mecanum wheel is mounted on the main shaft. A pair of bevel gears allows the motor, brake, and gearbox to be mounted at a right angle to the drive shaft. Bevel gears were selected instead of worm gears because bevel gears can be backdriven, whereas worm gears cannot. This feature is important because it allows the OTP to be towed. The motor, brake, and gearbox will all be commercially produced items. The drive electronics for the motors will also be commercially produced items, due to the high voltage and current requirements of the drive system. The drive electronics will be mounted as close to the motor as possible, probably inside the motor's protective case (shown in light gray in the figure below) to reduce the EMI emitted from the cables.



**Figure 19: Schematic of Omnidirectional Wheel Drivetrain,  
Top View (above) and Side View (below)**

This right angle drivetrain layout has two main advantages over an in-line shaft arrangement. The first advantage is related to vehicle width. The minimum width of the vehicle in the in-line arrangement is set by the wheel width, main shaft length, and the length of the motor, brake, and gearbox assembly, which can be between 10 and 16 inches. For the right angle drive, this minimum width is set by the wheel width and the motor diameter, which ranges from 3 to 8 inches. Thus, the Omnidirectional Transport Platform can be made narrower utilizing the right angle drive. The second advantage of the right angle drive is that it can more easily

accommodate a horseshoe design with the opening on the narrow side. Figure 20 shows a layout of the OTP comparing the right angle drive with the in-line shaft arrangement. If the OTP with the right angle drive were configured in a horseshoe, the natural opening for a lift platform which can be lowered to the floor would be on the narrow ends, the left or right end in the schematic. If the in-line shafts were configured in a horseshoe, the natural opening would be along the wide side, the top and bottom of the schematic. The opening on the narrow end is more consistent with the transportation of long, slender items such as missiles.



**Figure 20: Comparison of Drivetrain Layout, Right Angle vs. In-Line Shaft**

The Phase II system of the OTP will be powered by replaceable battery packs. The system will feature 2 or 3 banks of batteries. The platform will only draw power from a single battery bank at a time. The multiple battery banks increases the working time of the platform on a single charge. This design also allows for "hot-swapping" - changing a battery without powering down the system. Since only 1 battery bank is in operation at a time, the other battery bank(s) can be replaced without affecting the system performance.

Multiple battery packs provide more flexibility in the design of the mechanical structure of the OTP. The battery banks can be arranged around the periphery of the horseshoe design. This allows for a large, unobstructed area for the working mechanism to reach all the way to the floor. The multiple battery packs also improve the reliability of the system by eliminating a single point power failure.

The working mechanism will be a scissors lift platform, pallet tines, missile cradle, or any other custom material transport hardware. The horseshoe configuration allows the working mechanism to be connected to the structural members of the chassis. The working mechanism has an unobstructed range of motion all the way down to the deck. This will make loading and unloading the OTP easy.

## B. Design Specification

Parameter	Units	Specification	Notes
Capacity	lbs	6000 12000	4000 min for horseshoe config 9500 min for box config
Weight	lbs		
Length	in		
Width	in		
Height	in	20	24 max
Ground Clearance	in	3	hangar bay fire door sill
Speed - Max	mph	5	
Speed - Typical	mph	3	
Safety Factor (design)		3	designed against yield
Safety Factor (tested)		2	designed against yield

**Figure 21: Major System Parameters, As Described In The Systems Innovation and Development Guidance Document (SIDGD)**

Parameter	Units	Specification	Notes
Ramp Angle	deg	20	no payload, at gross vehicle weight
Max Slope	deg	8	at full load
Tire Contact Pressure	psi	280	
Obstacle height	in	2	hoses, tie down chains
Deck Edge Gap	in	3	elevator
<u>Stability</u>			
Static Angle	deg	15	with maximum payload
Vertical Drop	in	2	with maximum payload
Ship Pitch	deg	2	
Pitch Period	sec	8	
Ship - Roll	deg	11	
Roll Period	sec	18	
Duration of Operation	hr	8	
Recharging Time	hr	0.5	can use replacable energy packs
Mean Time To Repair	hr	1.5	
Color		white	color 17925 of FED-STD-595
Duty Cycle	hr	8	Shift duration
Standing Still and Idling	hr	1.5	19%
Creep Motion	hr	1.5	19%
Walking Speed	hr	2	25%
Dash Speed	hr	2	25%
Off	hr	1	13%

**Figure 22: Additional Specifications of Phase II Design from SIDGD**

Max Pressure	280 psi
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Horseshoe Config		Box Config	
Payload	6000 lbs	Payload	12000 lbs
Vehicle (est)	2500 lbs	Vehicle (est)	5000 lbs
GVW	8500 lbs	GVW	17000 lbs
Number of Wheels	4	Number of Wheels	4
Weight per wheel	2125 lbs	Weight per wheel	4250 lbs
Required Tire Patch Area	7.59 in <sup>2</sup>	Required Tire Patch Area	15.18 in <sup>2</sup>

**Figure 23: Contact Pressure Calculation, Based On SIDGD**

### C. User Interface

The user interface is contained in a single box which is rigidly mounted to the chassis. The height of this box is adjustable by the user. When not in use, the joystick and pedestal will fold down, laying against the chassis. The joystick will be programmed to control the platform such that the center of rotation is at the location of the joystick. The motors will simply magnify the forces and torques the user places on the joystick. This will make the device very intuitive to use. If the user twists the joystick, the platform will spin about that point exactly as if the user was extremely strong and was pushing the platform manually. For maximum flexibility of operation, the joystick pedestal can be mounted on either the left or right side of the platform.

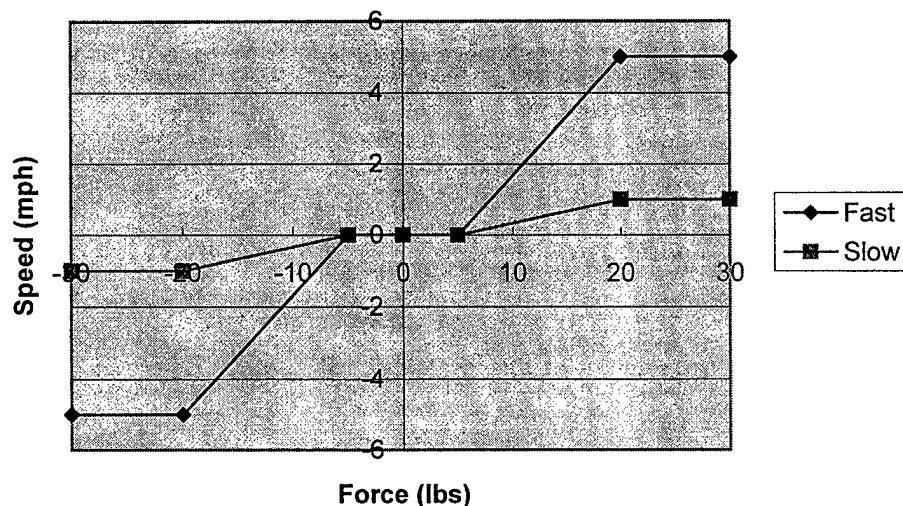
The user interface box connects to the drive electronics. There is a series of switches which will control the operating modes. The operating mode controls how the vehicle responds to the joystick input. The toggle switches include:

- fast / slow (for movement or precision alignment)
- brake release (for towing and/or manual pushing)
- auxiliary operations (for controlling the scissors lift, for example).

The joystick is a non-compliant force sensor which measures the force and direction the user is pushing. The joystick purchased for the prototype can measure 2 degrees of freedom. A third degree of freedom will be added to the joystick to measure rotation for the Phase II. The joystick is set to respond with the following pattern:

- below the minimum threshold - no movement and the brakes are locked
- above minimum threshold but below maximum - speed is proportional to force applied
- above maximum threshold - speed is maximum

This pattern is clearly shown in Figure 24. The two curves represent the speed set by the toggle switch, fast or slow. Fast would be used when moving the platform long distances, such as across the hanger bay to the flight deck. Slow would be used for precise positioning such as aligning the skid to remove or install an airplane engine.



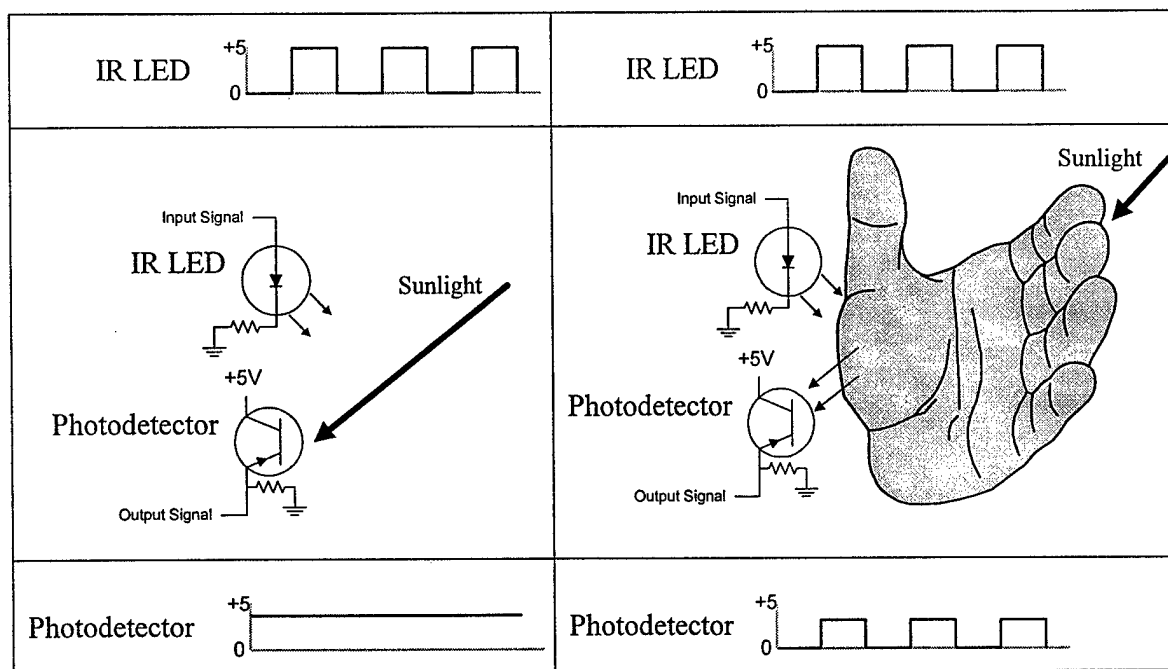
**Figure 24: User Input Force vs. Speed Relationship**

The final element of the user interface will be the deadman and emergency stop switches. These switches and sensors will prevent the platform from moving at undesired times. There will be 4 emergency stop switches located at each corner of the OTP. When any of these switches are triggered, the device will come to an immediate stop. Power to the motors will be shut off, and the failsafe brakes will be engaged. This will cause the platform to stop as quickly as possible. This act of stopping rapidly may cause some shifting of the payload. Although there is a safety concern of such a violent and rapid stop, this may be the best action in the case where an emergency stop is necessary. The deadman switch provides a second control for the stopping of the vehicle. When the deadman is released, the software will perform a controlled deceleration, utilizing the motors to safely slow the vehicle to a speed where the brakes can be applied to fully stop the vehicle.

In the Phase I prototype, the deadman is a switch that the operator is required to hold in order for the platform to respond to joystick commands. In the Phase II system, this switch may be replaced by an optical system. The optical system consists of an infrared light emitting diode (IR LED) and a photodetector, either a photodiode or phototransistor. The photodetector measures the amount of IR light. A diagram of the optical sensor is shown in Figure 25. The IR LED and photodetector are mounted on the joystick handle. The IR LED is pulsed, alternated between on and off. The amount of IR light is measured by the photodetector and is compared to the state of the IR LED. When the user is holding the joystick, he will be covering both the IR LED and the photodetector. His hand will shield the photodetector from the ambient light. Thus the photodetector will only measure IR light which reflects off the user's hand. This diagram is shown in the right side of Figure 25. When the user releases the joystick, the light from the LED will not be reflected and the photodetector will only measure the ambient levels of IR light, e.g. sunlight. This graph is shown in the left side of Figure 25. Therefore, by looking at the pattern of the output signal from the photodetector, we can determine if the user is holding the joystick or not. Cybernet has used this method of optical deadman switches to provide an intuitive



method for implementing the deadman switch without causing finger strain or fatigue, which can occur when the user is required to hold a physical button for the duration of an activity.

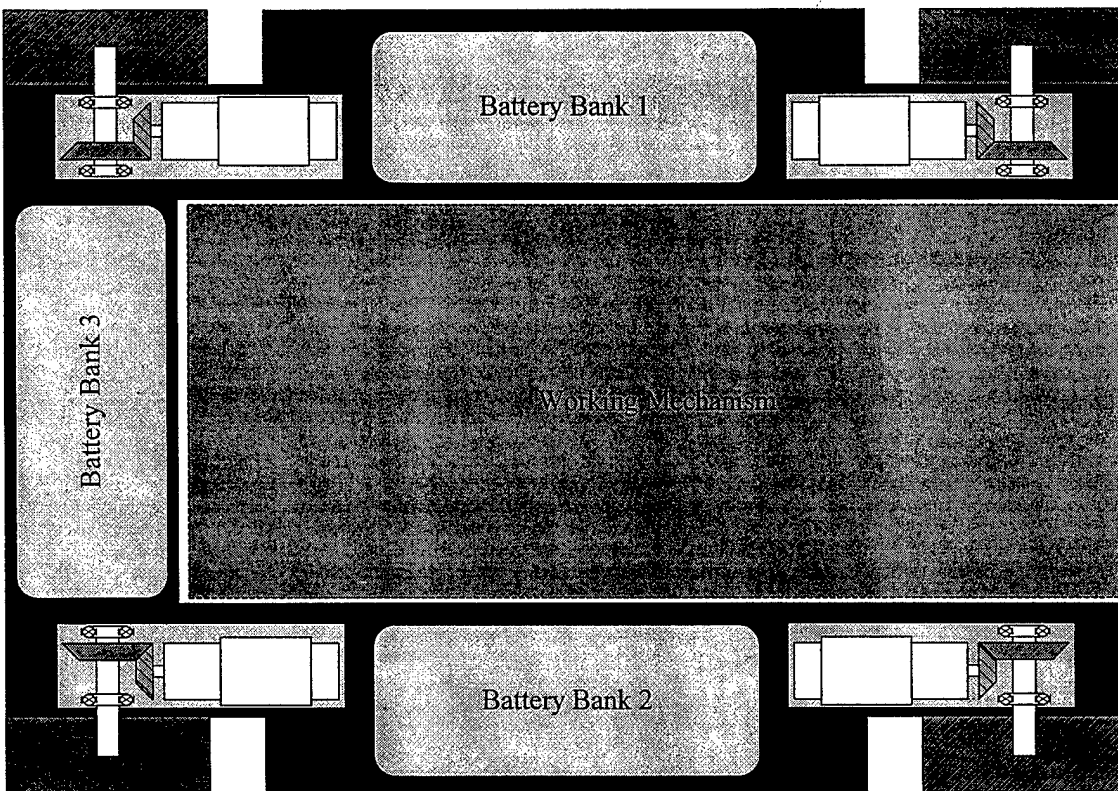


**Figure 25: Optical Deadman**

#### **D. Power System**

The Phase II system of the OTP will be powered by replaceable battery packs. The system will feature 2 or 3 banks of batteries. The platform will only draw power from a single battery bank at a time. The multiple battery banks increases the working time of the platform on a single charge. This design also allows for “hot-swapping” - changing a battery without powering down the system. Since only 1 battery bank is in operation at a time, the other battery bank(s) can be replaced without affecting the system performance.

Multiple battery packs provide more flexibility in the design of the mechanical structure of the OTP. As shown in Figure 26, the battery banks can be arranged around the periphery of the horseshoe design. This allows for a large, unobstructed area for the working mechanism to reach all the way to the floor.



**Figure 26: Top View of OTP Showing Battery Bank Locations**

The multiple battery packs also improve the reliability of the system by eliminating a single point power failure. It is highly unlikely that all 3 battery packs will be out of power, disconnected, or removed. The OTP will monitor the state of each battery. When one battery is drained to 10% of its maximum, the OTP will switch to drawing power from one of the other 2 battery banks. The OTP will also inform the operator which battery bank is low. The 10% reserve power will ensure that the platform will have sufficient power to move to the battery charging station under its own power, even when all battery banks are depleted.

There are a variety of battery chemistries that are currently available. These include Nickel Cadmium (NiCd), Nickel Metal Hydride (NiMH), Lead Acid, Lithium Ion (Li-Ion), and Lithium Polymer (Li-Polymer). Figure 27 shows a comparison of relevant electrical characteristics of the various battery chemistries. Li-Ion and Li-Polymer are quite new to the market place. They have the highest power density, but they are also the most expensive. NiMH is also a fairly new chemistry to the market and also carries a high price tag for its high power density. Since the weight of a battery for applications of ground rolling vehicles is not as critical as cost and performance, NiCd and Sealed Lead Acid batteries are the two best choices.

Battery Type	Nickel-Cadmium	Nickel Metal Hydride	Sealed Lead Acid	Lithium Ion	Lithium Polymer
	NiCd	NiMH	SLA	Li-ion	Li-Polymer
Energy density (Wh/Kg)	50	75	30	100	175
Cycle Life (typical)	1500	500	200-300	300-500	150
Cell voltage (nominal)	1.25V	1.25V	2V	3.6V	1.5V
Battery Cost	low	medium	very low	very high	high
Estimated, cost ref.	50	80	25	100	90
Est. per cycle cost ref.	0.04	0.16	0.10	0.25	0.60

**Figure 27: Battery Chemistry Comparison**

NiCd batteries have great load current delivery capabilities because of their low internal resistance. Since mobile platforms do not require extreme bursts of current, this feature is not an advantage. One major disadvantage of NiCd batteries is what is commonly referred to as the "Memory Effect". There are actually two different phenomena that are referred to as battery memory. The first is cyclic memory: referring to how the battery "remembers" how much it was discharged the last time. This phenomenon plagued the first generation of NiCd batteries but recently has been all but eliminated. The second phenomenon that is referred to as "memory" is due to crystalline formation on the battery plates. As these nickel/cadmium crystals grow they reduce the performance of battery significantly. Only proper "exercise" of the batteries will break down the crystalline formations for maximum performance of the batteries. This exercising or conditioning requires the batteries to be fully discharged and fully recharged. If this is not done at proper intervals, it may have to be done repeatedly to break down all the crystalline formations. Due to NiCd's high exercise / maintenance requirements and higher initial investment costs, nearly all ground rolling vehicles use a form of Lead Acid batteries.

Lead Acid batteries are grouped into roughly three basic categories Automotive, Traction, and Stationary. The most common lead acid battery is the automotive variety, used mainly in cars for engine starting. These batteries have thin battery plates and are designed for short periods of very high current output. They require immediate recharging and typically can not be discharged to more than 75% of their total capacity to maintain full performance. Traction batteries on the other hand have thick battery plates, are designed to be nearly fully cycled, and can be used in environments with high physical shock and vibration. Stationary batteries are designed mostly for backup power systems and are constructed with thin solid battery plates and less power density. These batteries are designed to be kept at a full charge until used, and if maintained properly, can last as long as ten years.

There are two basic types of lead acid batteries: flooded and sealed. Flooded batteries have free flowing liquid electrolyte. Sealed batteries have their electrolyte suspended and sealed. Flooded batteries require the battery to be kept in an upright position or they can spill and leak their electrolyte. These batteries also need routine maintenance. During charging, gassing takes place where hydrogen and oxygen build up on opposite battery plates and are discharged as gasses. This means that over time the electrolyte loses water. This water must be replaced or the battery

will dry up and be permanently damaged. Sealed Lead Acid (SLA) batteries, as their name implies, are sealed so they will not spill or leak their electrolyte. This is achieved by both sealing the battery case and by suspending the battery electrolyte between the plates. Since their electrolyte is sealed and suspended, SLA batteries require no electrolyte maintenance.

Gel cells are the most common SLA batteries. Gel cells use fumed silica to gel the electrolyte and hold it in place between battery plates. Gelling the electrolyte increases its resistance and thus lowers its charge and discharge rates, increasing recharge time and lowering peak current delivery. GNB makes a SLA battery that suspends its electrolyte in compressed absorbed glass mat separators. This improves internal resistance and gas recombination, allowing for faster recharges and higher peak current delivery. GNB's Champion Batteries designed for mobile transport pallets provide full shift performance to an 80% depth of discharge equal to 1.90 volts per cell. Batteries come in 6 and 12 volt configurations with 300-400 cycles and a 2.5 year life span. These batteries will accept periods of short "opportunity charging" as small as ½ hour (plus an additional cool down period), allowing them to be charged during idle time in the middle of a working period. Specially designed chargers can charge a fully discharged battery within eight hours.

Part Number	(volts)	6 Hour Rate		Dimensions (inches)			(lbs.)
	Voltage	AMP-HRS	KWH	Length	Width	Height	Weight
M83CHP12V24	12V	80	0.94	10.25	6.85	8.8	55
M83CHP12V27	12V	95	1.1	12.05	6.85	8.8	65
M83CHP06V27	6V	195	1.15	12.05	6.85	8.8	67

**Figure 28: Champion Deep Cycle Battery Specifications**

Manufacturers of Sealed Lead Acid Batteries:

- GNB (Champion)
- Excite (Work Hog)
- Torjan
- Surette
- Eagle-Picher
- Yuasa
- Power Sonic
- Panasonic

#### **E. Electronics**

The Phase II system will feature much of the same architecture as the Phase I system. The two major differences will be enhanced self-diagnostic tests and distributed drive electronics. Due to the high current and voltage requirements of the Phase II system motors, the drive electronics will be an existing, commercially available product. These drive systems have been developed and refined by motor manufacturer over the years and have been optimized for the high current and voltage systems which we will need to drive the payloads.

The drive electronics will be distributed, meaning that each motor will have its own drive electronics unit, mounted in close proximity to the motor itself. This will serve to reduce the

EMI (electro-magnetic interference) emissions from the OTP platform. EMI can be caused when elements of the circuit acts as antennas or beacons of noise. Emissions are particularly strong in circuits which have rapid switching of current. In our system, there are 4 major possible sources of EMI emissions: the digital logic of the main control hardware, the motors themselves, the drive electronics for each motor, and the cables. The main control electronics board itself will have emissions of not more than a notebook computer. But since the main control electronics will be mounted in a metal box, the EMI from this source will be all but eliminated. The motors are not a major source of EMI because the currents which flow through the motor coils are fairly steady. The drive electronics will be mounted near the motors and also shrouded by a metal case, preventing emissions. The final source would be cables, particularly the cables connecting the motors to the drive electronics, since those cables have the highest currents in them. The cables themselves will be shielded, to reduce their susceptibility to outside EMI. The cable length will be minimized by mounting the drive electronics near to the motor. Furthermore, the entire motor, drive electronics, and cables could be mounted in a single box to contain all the EMI from those 3 sources. Cybernet has experience with EMI testing of our force feedback joystick devices. We have access to local testing facilities at the University of Michigan.

## F. Operating Modes and States

The Phase I prototype displays a portion of the states which will be present in the Phase II OTP system. Figure 29 shows the operating mode flowchart of the system checks and resulting behavior of the Phase I system. These operating modes are described in greater detail in the following sections.

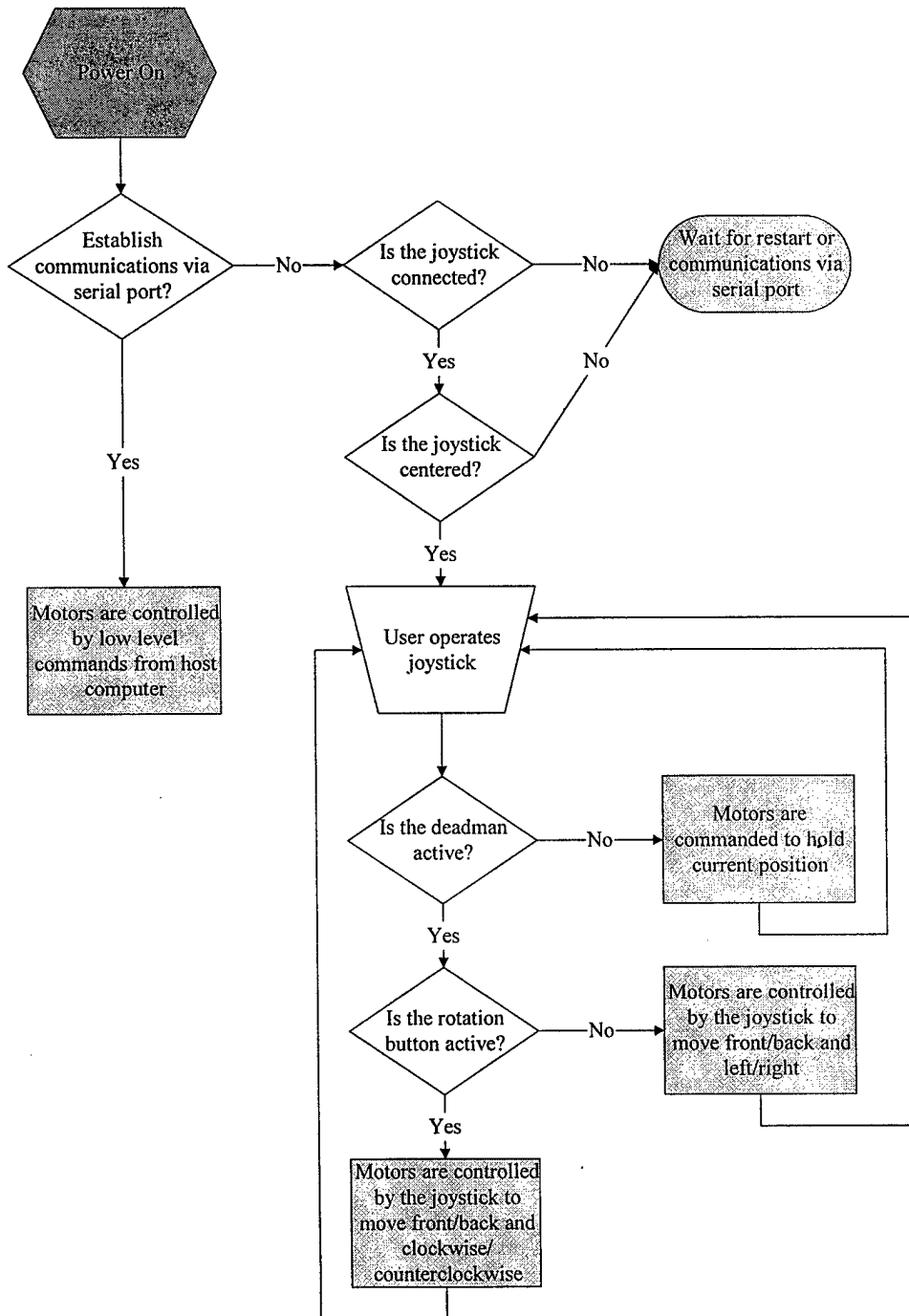


Figure 29: Flowchart of Software Checks in Phase I Platform

## 1. Power Off

When the prototype is powered off, the motors are not engaged, so the unit may be pushed or towed easily.

In the Phase II system, there will be failsafe brakes with a manual override. When the power is off, the brakes will be locked, preventing the platform from moving. The manual override is to allow the OTP to be towed in case of loss of power. Under this configuration, the brake will not engage until the manual override is released.

## 2. Startup

The phase I system performs several checks during start-up. First, it checks the serial port to try and establish a communications link with a computer. If this is successful, then the OTP is controlled by the host computer. This feature could be useful for a semi-autonomous OTP, with that host computer integrating the additional sensors and processing power required to perform navigation, collision avoidance, and path planning. If the communications link is not established, then the system checks for a joystick. If the joystick is connected and the centered values are within an acceptable range, the platform will respond to joystick input. The software checks for the centered value of the joystick to test to see if the joystick is working properly. This process is depicted in Figure 30.

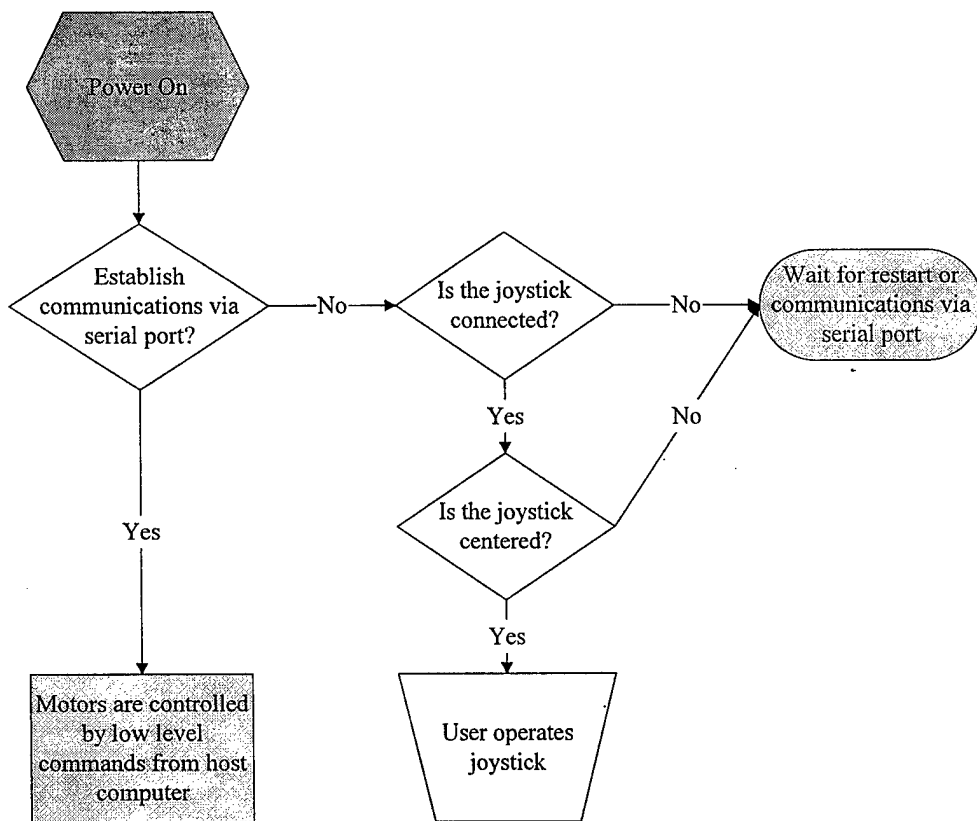
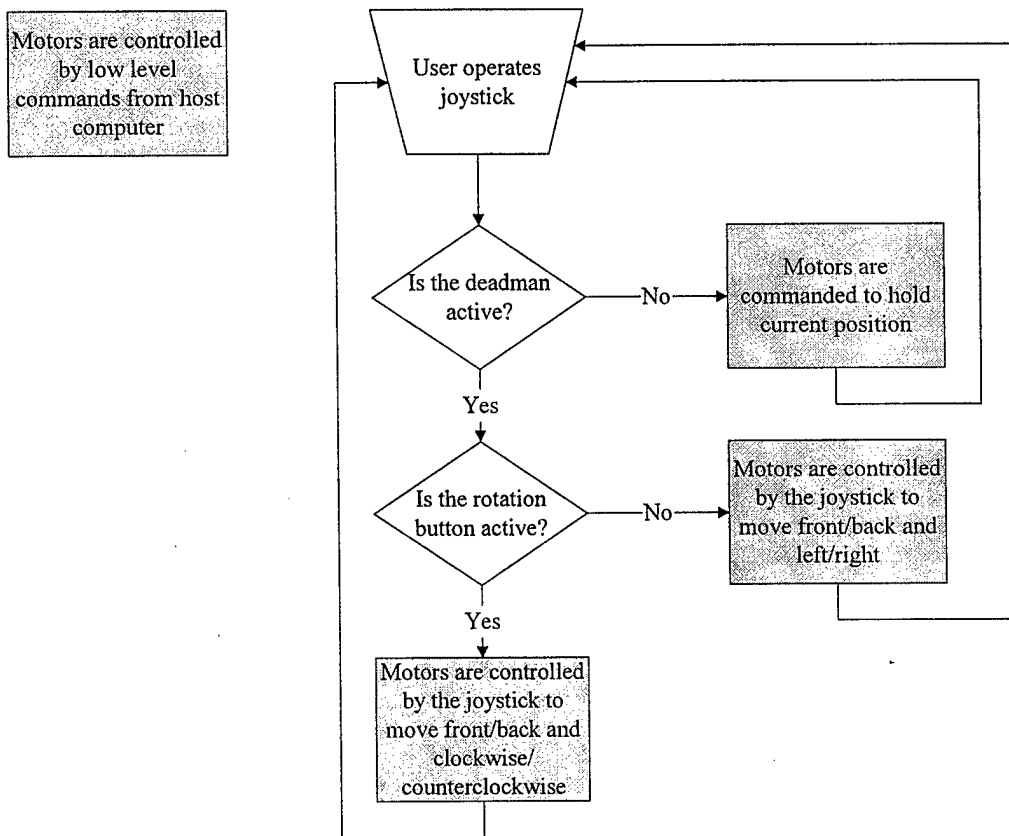


Figure 30: Startup Operating Mode of Phase I System

### 3. Fully Operational

After the startup procedure is complete, the phase I prototype operates in either of two modes - joystick control or host computer control. The host computer control is fairly simple - the motors respond to the velocities commanded by the host computer. Any position feedback or closed loop control is the responsibility of the host computer. When the platform is under joystick control, the first thing the software checks for is the deadman. If the deadman switch is held down, the motor drivers are active and allow the platform to move. At the instant the deadman switch is released, including the joystick becoming unplugged, the motors stop driving and hold their current position. Since the Phase I prototype does not have integrated failsafe brakes, the motors are used to actively maintain the current position. The Phase II system will have failsafe brakes, which would be engaged any time the deadman switch is not being held.



**Figure 31: Fully Operational Mode of Phase I System**

The second check the software does during the joystick controlled mode is to look at the state of the rotation button. This button is required because the joystick interface only has 2 degrees of freedom. The rotation button tells the control software to interpret the left/right signal from the joystick as clockwise/counter-clockwise rotation. The forward/backward motion is unaffected by the state of the rotation button. In the Phase II system, the joystick interface will be enhanced to include the rotation measurement on the joystick itself, thereby making the rotation button obsolete.



The Phase II system will be equipped with both deadman and emergency stop switches. These switches and sensors will prevent the platform from moving at undesired times. There will be 4 emergency stop switches located at each corner of the OTP. When any of these switches are triggered, the device will come to an immediate stop. Power to the motors will be shut off, and the failsafe brakes will be engaged. This will cause the platform to stop as quickly as possible. This act of stopping rapidly may cause some shifting of the payload. Although there is a safety concern of such a violent and rapid stop, this may be the best action in the case where an emergency stop is necessary. The deadman switch provides a second control for the stopping of the vehicle. When the deadman is released, the software will perform a controlled deceleration, utilizing the motors to safely slow the vehicle to a speed where the brakes can be applied to fully stop the vehicle.

#### *4. Shut Down*

The Phase I System does not perform any shutdown operations.

### **G. Degraded Operating Modes**

An important characteristic of a successful OTP design will be its ability to handle failure scenarios. One solution to any failure scenario is towing. There are three main scenarios when the OTP would need to be towed: fully operational but overloaded, loss of battery power, or degraded function. The OTP has a tow hitch located at the front of the vehicle. We would like to design the tow hitch with an embedded sensor which monitors if the platform is being towed. If this sensor is not practical or reliable, the user interface panel will have a switch to activate a towing mode.

In the case when the vehicle is overload (the motors are functional but not able to move due to excessive payload), all systems are assumed to be functional. When the tow vehicle is pulling the OTP, all of the wheels are not powered and the brakes are released, so that the wheels are allowed to turn freely. The rotation rates of the wheels are monitored by the control circuit. The only motions allowable in the towing mode are those possible with a conventional Ackerman steering - forward/backward motion with or without turning. If the control circuit measures a significant sideways velocity, then it will infer that the OTP is sliding sideways due to the rolling or pitching of the ship - an undesired motion. The rear two motors will be activated and actively driven to produce Ackerman-type motion, preventing the sideways slip. This condition can be demonstrated by deactivation of the front two motors on the Phase I prototype. The OTP behaves like a conventional vehicle, forward and backward are the same, but left and right motion is converted into clockwise and counter-clockwise turns.

If the vehicle has lost battery power, the electric failsafe brakes will be in their locked position, preventing any motion of the OTP. Each brake will have a mechanical manual release. Each of the brakes must be released in this fashion. The vehicle can be towed with all of the wheels moving freely. This may cause some difficulty during towing because the OTP can move in any direction, namely downhill in the case of ship pitch or roll.

The final scenario for towing would be in the case of degraded function. In this regime, the operator has the choice of setting the platform in tow mode and manually releasing the brakes on

the non-working wheels, or turning the platform off and towing the OTP as if it has lost battery power.

### *1. Full loss of Mobility Failure*

In this scenario, the platform must be towed to the repair shop, as described in the section above.

### *2. Partial Loss of Mobility Failure*

Due to the nature of the omnidirectional wheel design, only 3 of the wheel units are required for full mobility. The fourth wheel was included to improve stability. Thus, if any one of the 4 wheels should lose its ability to move, the system will still be able to exhibit omnidirectional motion. The two requirements are: 1) the disabled wheel is able to turn freely, and 2) the remaining motors have sufficient power and traction to move the platform. This degraded performance mode has been demonstrated with the Phase I prototype. We noticed that the platform maintained its ability to move forward and backward in a straight line, but when commanded to perform a pure sideways motion, the platform rotated slightly. This behavior was still controllable by the operator, it just required more concentration to compensate for the non-power wheel.

If a second wheel is also disabled, the usability of the platform is much more limited. If the two wheels form a same-direction pair, front left/rear right or front right/rear left, then the platform should be categorized as full loss of mobility. If the two wheels are an opposite direction pair, then the platform can still be operated, though no longer truly omnidirectional. If the pair of wheels are on opposite sides (i.e. both front wheels or both rear wheels), then the platform will drive like a conventional Ackerman steering vehicle. The system can drive forward/backward in a straight line, or turn left or right. The front/back command from the joystick are still executed the same way, but a sideways has exactly the same response as a rotation input - the result in both cases is turning about the midpoint between the two wheels. If the pair of wheels is on the same side (i.e. both right wheels or both left wheels), the system can drive left/right as before, but forward/backward and rotation both cause the vehicle to drive in a large radius turn. This could be sufficient mobility to maneuver the OTP into a location from which it can be towed for repair.

### *3. Main Computer or Major Subsystem Failure*

Since the OTP is equipped with failsafe brakes, any interruption in the deadman, control signal from the main computer, or loss of power will result in the immediate engagement of the brakes, causing the platform to stop. During start-up and normal operation, the main computer will continuously perform a series of self-tests to determine if the system is working properly. The main computer will have a watchdog timer, which requires the main computer to repeatedly update the timer. This watchdog ensures that the main computer is working correctly. If the main computer fails for some reason, it will not be able to update the watchdog timer, and the watchdog will restart the main computer. If the computer notices peculiar behaviors such as a high current draw, rapid changes in battery state, stalled motor, or erratic wheel velocity measurements, the computer will notify the operator and take whatever actions necessary to ensure the safety of the crew and the cargo. The main computer will have a bank of non-volatile

data storage, such as EEPROM, to record such information. This information can be retrieved during servicing to help identify the root of the malfunction.

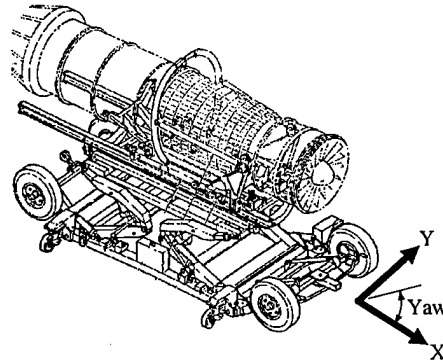
## H. System Design - Omnidirectional Positioning Caster (OPC)

The Omnidirectional Positioning Caster (OPC) would be a drop-in replacement for the positioning casters currently employed on the ETU-110/E. The OPC will be a driven omnidirectional wheel which will allow the mechanic to position the trailer without requiring physical pushing or manual adjustment of the rail position. The Omnidirectional Positioning Caster would be a modular upgrade of the caster assembly, allowing for simple replacement and/or removal. This development path would allow us to focus on the new functionality (omnidirectional wheel) without having to redesign the entire chassis, mounting points, and tow arrangement of the skids. This design path also would provide a lower upgrade cost to existing ships in the fleet.

The following two lists compare the engine removal scenario using the ETU-110/E and the ETU-110/E with OPC. As we can see, the OPC reduces the amount of repositioning required, thereby reducing the time it takes for a crew to remove or install an engine.

For the purposes of these scenarios, X refers to motion forwards and backwards as rolled on the main 4 wheels.

Y direction refers to side to side motion, i.e. motion not possible with the main wheels on the ground. Yaw refers to the orientation of the trailer relative the plane.



**Figure 32: ETU-110E with Positioning Caster**

ETU-110/E with OPC	ETU-110/E with positioning caster
<ol style="list-style-type: none"> <li>1. Trailer is towed/pulled into a location near the airplane using 4 main wheels.</li> <li>2. OPCs are installed and main wheels are raised.</li> <li>3. Trailer is driven into position (X,Y, and yaw).</li> <li>4. Rails are raised.</li> <li>5. If the rails are not aligned, the trailer is driven into the proper position using the OPC.</li> <li>6. Engine is removed.</li> <li>7. Trailer with engine is driven to new location.</li> </ol>	<ol style="list-style-type: none"> <li>1. Trailer is towed/pulled into a location near the airplane using 4 main wheels.</li> <li>2. Positioning casters are installed and main wheels are raised.</li> <li>3. Trailer is pushed into position (Y and yaw).</li> <li>4. Rails are raised.</li> <li>5. If the rails are not aligned with the engine, lateral adjustment is made (+/- 2 inches).</li> <li>6. If more lateral motion is needed, trailer is pushed into position (Y and yaw).</li> <li>7. If X direction adjustment is needed, the 4 main wheels are lowered, return to step 1.</li> <li>8. Engine is removed.</li> <li>9. Trailer with engine is pushed/towed to new location.</li> </ol>

## Appendix A: Problem Background

Currently, naval personnel use manually maneuvered skids, like those shown Figure 33, to perform weapons handling. These skids are either moved into place by hand, or are towed by general purpose vehicles, such as an aircraft tow tractor. Figure 34 shows a lift trailer used in handling aircraft engines. The OTP is intended to replace these types of equipment - skids, trailers, and the tow tractors used to haul them around. The OTP would be utilized to function as a generic platform upon which payload-specific hardware could be mounted. This would allow the OTP to be configured for use over a wide range of applications:

- Weapons / stores transporting and some weapons / stores loading.
- Installation, removal, and transport of aircraft fuel tanks.
- Installation, removal, and transport of aircraft engines.
- Transport and handling of aircraft engine preservation cans.
- Installation, removal, and transport of large and medium-sized weapons replaceable assemblies (WRAs).
- General aviation materiel handling and transporting.

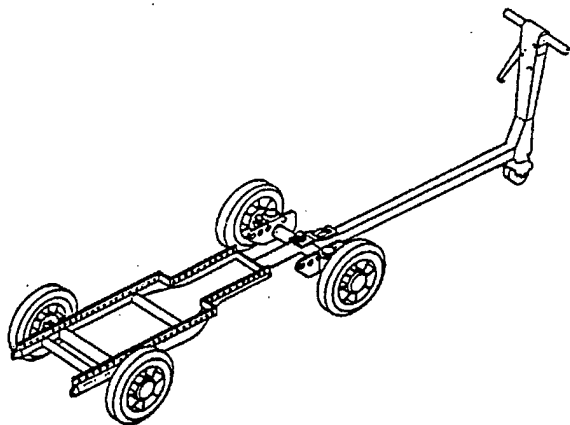


Figure 33: MHU 191

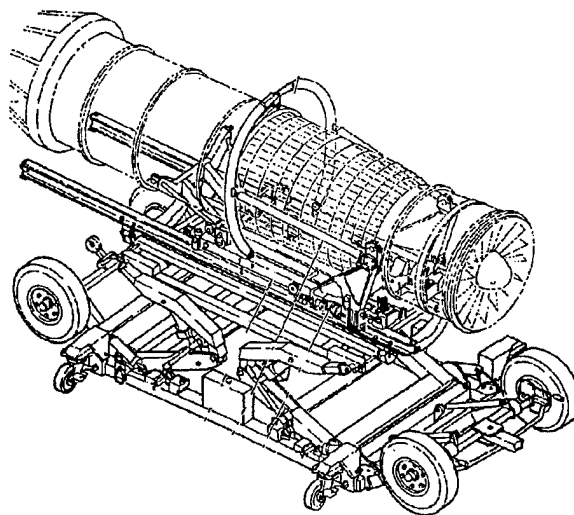


Figure 34: Etu-110/E Aircraft Engine Lift Trailer, Shown Carrying Engine

In November 1993 the Navy performed tests on the mobility platform concept and issued a report titled "Omni-Directional Vehicle (ODV) Operational Field Evaluation". This report made several conclusions about the use of omnidirectional wheels for in-ship transportation of materials.

1. Omnidirectional technology with regard to mobility and maneuverability of the basic ODV platform was sufficiently demonstrated to fleet (shipboard and shore based ) "0" level operators and maintenance personnel.
2. The extension of OD technology to the F404 engine change function relative to ease of operation, controllability, precision, manpower requirements, and time comparison was sufficiently demonstrated to F/A-18 squadron jet engine and GSE shop personnel.
3. The ODV concept has several air-platform interface potential applications.

This report also ended with two recommendations:

1. Given the positive aspects of maneuverability, precision handling, and time and manpower savings, it is recommended that the ODV concept be further developed into a workable vehicle, be it engine handling, weapons handling, or fire fighting.
2. Future designs should accommodate the comment within the body of this report; specifically with regard to height, servicing, and shipboard compatibility.

This project will focus on both of these recommendations. Suggested improvements from testing can be grouped into two categories: omnidirectional wheel improvements and general system design improvements.

#### *Omnidirectional Wheel Improvements:*

- better tire surface (not rubber) which lasts longer against non-skid deck surface
- improve traction on oil slick deck surfaces
- eliminate contact between the deck tie-down fittings and the structural metal of the wheel assembly

#### *General System Design Improvements:*

- lower platform height - move wheels outboard to allow platform deck to be lower
- improve suspension - not as choppy, better vibration damping
- employ fast/slow modes of operator control - joystick was too sensitive
- increase component accessibility and provide external test points
- ensure compatibility with battery charging equipment
- stronger tow rings
- permanently attached tow rings, so they can't get misplaced
- ensure safety of electrical systems operated around jet fuels

## Appendix B: Omnidirectional Wheel Technology

Omnidirectional wheel technology is the fundamental technology for the OTP. Research in this area was the focus of the Phase I activity, culminating in a prototype of an omnidirectional platform. These omnidirectional wheels allow the platform to be driven in any direction from any orientation. This provides significant improvement in mobility around objects and decreases the time necessary to correctly position the payload during aircraft servicing or weapons loading. This section presents an overview of three classes of omnidirectional wheels: Mecanum wheel, steerable driving wheels, universal wheel, and orthogonal-wheels.

We selected the Mecanum wheel as the omnidirectional wheel technology for this project. We did not choose the steerable driving wheel because of tire wear due to scrubbing. We did not choose the orthogonal wheel concept because of poor performance of this technology during obstacle traversal. These wheels work best on flat, smooth surfaces. We did not select the universal wheel because of the sharp transitions between different idlers, which would result in a periodic jarring and vibration to the carried load. The Mecanum wheel provides a smoother ride than the universal wheel, reduces tire wear as compared to the steerable driving wheel, and has better obstacle traversal performance than the orthogonal wheel concept.

### 1. *Mecanum Wheel*

This class of wheel is called the Mecanum wheel or the Ilon wheel. Like the universal wheel, the Mecanum wheel has passive rollers mounted on the rim of the drive wheel. The universal wheel has the passive rollers mounted 90 degrees to the axis of rotation of the drive wheel. The Mecanum wheel has the rollers mounted at an angle of 45 degrees, as seen in Figure 35. This allows the rollers to be spaced closer together so that the wheel has an unbroken round profile, as shown in Figure 36. This allows a smoother transition from one roller to the next, making the motion less jarring for the payload.

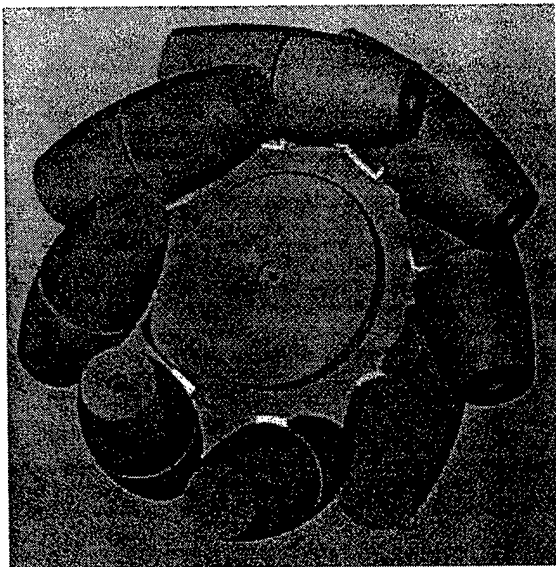


Figure 35: Mecanum Wheel

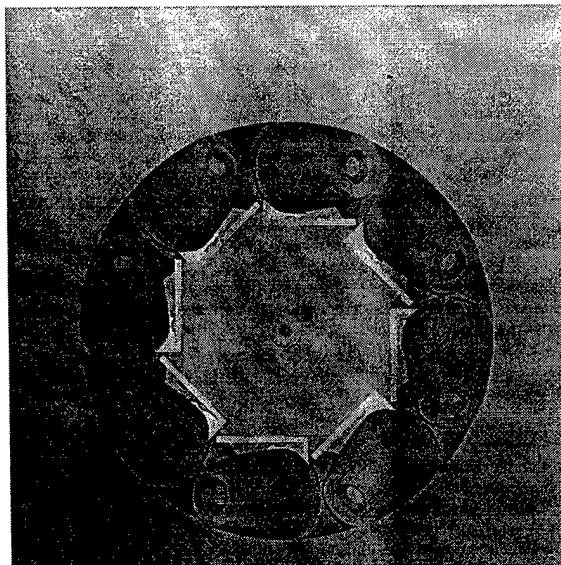


Figure 36: Mecanum Wheel, Side View

The shape of the Mecanum wheel can be constructed by the following process<sup>2</sup>:

1. Choose a roller axis.
2. Pick any point on this axis. Varying this point generates the shape of the entire roller.
3. Pass a perpendicular line from the wheel axis through that point, extending to the cylinder which defines the nominal wheel outer diameter.
4. Since this point on the cylinder surface must also lie on the roller surface, transform this point into the roller coordinate system (at the location  $x_1, y_1, z_1$ ).
5. Calculate the distance from that point to the roller axis (distance =  $\sqrt{x_1^2 + y_1^2}$ ). This is the roller radius at  $z_1$ .
6. Return to step 2, choosing a new point.

The curve defining the roller can be found through a parametric equation in terms of  $t$ , which will vary from 0 to the maximum roller length.

Known Dimensions:

$$R = 1/2 * \text{wheel\_diameter}$$

$$b = 1/2 * \text{idler\_roller\_diameter}$$

$$e = \text{attack\_angle\_of\_idler\_roller}$$

$$\text{max\_roller\_length} = 1 / \sin(e) * \sqrt{b * (2R - b)}$$

$$0 \leq t \leq \text{max\_roller\_length}$$

$$c = R / \sqrt{(R - b)^2 + t^2 * \sin^2(e)}$$

$$x_1 = (c - 1) * t * \sin(e) * \cos(e)$$

$$y_1 = (c - 1) * (R - b)$$

$$z_1 = c * t * \sin^2(e) + t * \cos^2(e)$$

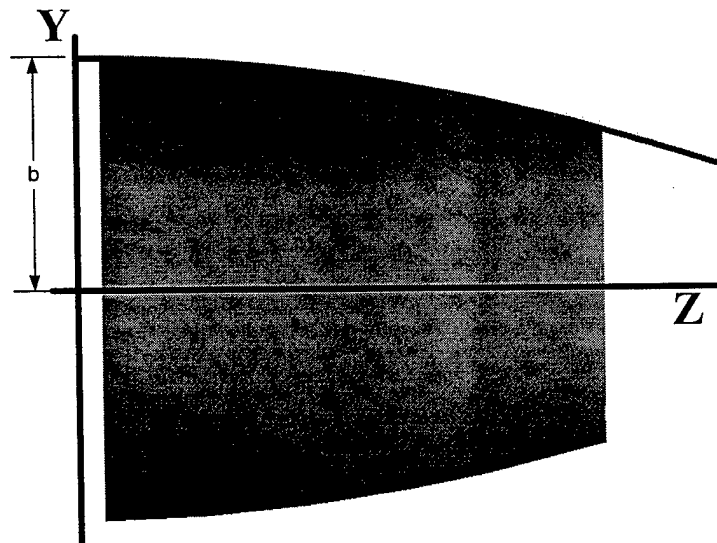
$$\text{local\_radius} = \sqrt{x_1^2 + y_1^2}$$

In the roller coordinate system:

$$x=0$$

$$y=\text{local\_radius}$$

$$z=z_1$$

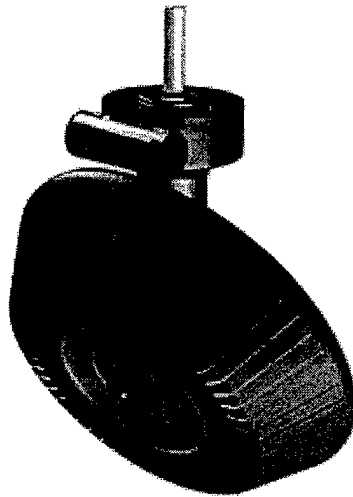


**Figure 37: Equations of Idler Roller Profile**

<sup>2</sup> Lapin, Brett, Stephen Dickerson, and Wiley Holcombe. Omnidirectional Vehicle Survey and Analysis. Georgia Institute of Technology, February 3, 1990.

## 2. *Steerable Driving Wheels*

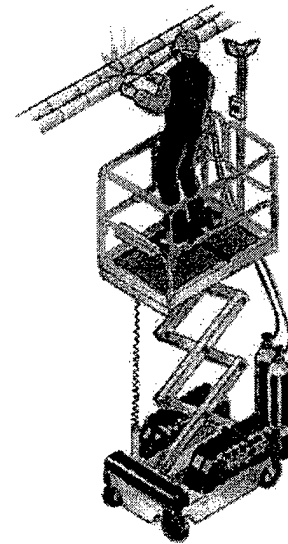
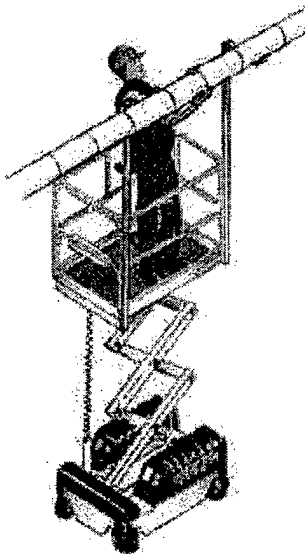
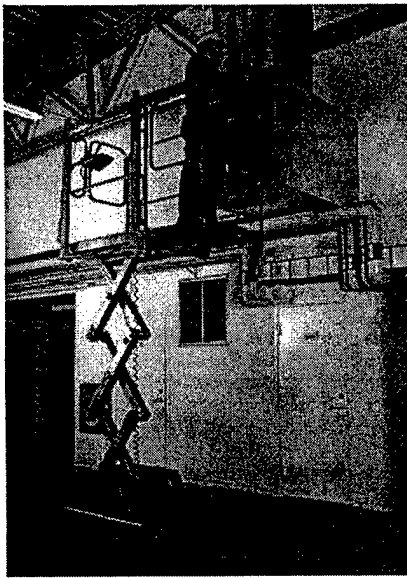
This class of omnidirectional wheels works by having two independently steerable driving wheels. Each wheel can be driven about its main axis of rotation. Each wheel assembly can be steered and thus change the wheel's direction relative to the platform's orientation. This steering method requires the wheel to be rotated about a vertical axis. For vehicles with heavy payload or wide tires, this may generate significant friction or sliding forces which lead to decreased performance and accelerated tire wear. Since each wheel's direction and orientation determine the vehicle translation speed, direction, and turning rate, the two wheels must be closely controlled to ensure a coordinated effort. This need for coordination is so high that a slight error in the steering control will result in tire slippage and performance loss.



**Figure 38: MaxWheel, by MaxMove**

One variation of the steerable driving wheel is made by MaxMove. The MaxWheel design features a conical tire and two motors per wheel, and shown in Figure 38. The drive motor is attached to the drive shaft to propel the conical wheel. The drive shaft has a vertical section, as seen at the top of Figure 38, and an angled section, to align with the axle of the wheel. The drive shaft is mounted inside the steering post, which, in turn is mounted inside the wheel housing. A second motor is mounted to the wheel housing and is perpendicular to the vertical shaft. This second motor controls the direction of the wheel by rotating the steering post inside the wheel housing. The design of the steering post and gearing automatically causes the wheel to turn whenever the direction of the wheel is changed. This reduces the amount of friction and thus increases tire life. Although the angled wheels reduces scrubbing during turning, it has higher scrub during straight-line motion than a conventional wheel. The MaxMove company utilizes this wheel on its product line of workstations, which are shown in Figure 39. MaxMove is currently working on developing a workstation for the British Navy to perform helicopter maintenance onboard their ships. In September 1999, MaxMove was performing stability tests of the workstation on board a platform set to pitch and roll to simulate ship motion. They have not yet completed tests to determine the durability of the tire on shipboard anti-skid.





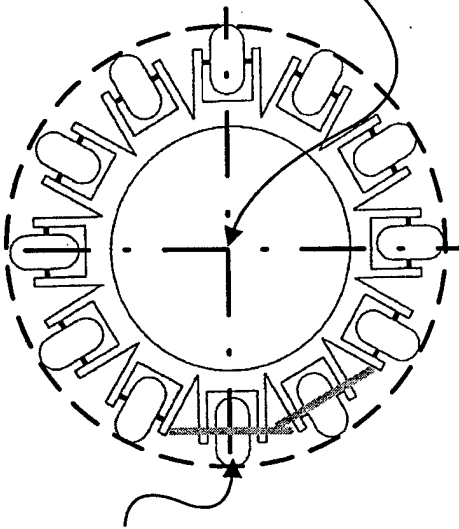
**Figure 39: MaxMove Workstations, As Used In Building Construction**

### 3. *Universal Wheel*

The universal wheel was designed to address the steerable wheels weakness on friction and inter-wheel constraints. The universal wheel is a “wheel within a wheel” concept. The heart of the assembly is the main drive wheel. This wheel is controlled to be driven like a conventional tire, it rolls about its main axle. The direction this wheel rolls is called the constrained direction. A series of smaller wheels make up the perimeter of the main wheel and form the contact surface between the main wheel and the ground. These smaller wheels are mounted on free spinning shafts whose axis of rotation is perpendicular to the main axle. This allows the small wheels to rotate when there are any sideways forces on the main wheel. The universal wheel is unconstrained in the direction of movement along the main axle, since the small wheels allow for free movement along this direction. The universal wheel is shown in Figure 40.

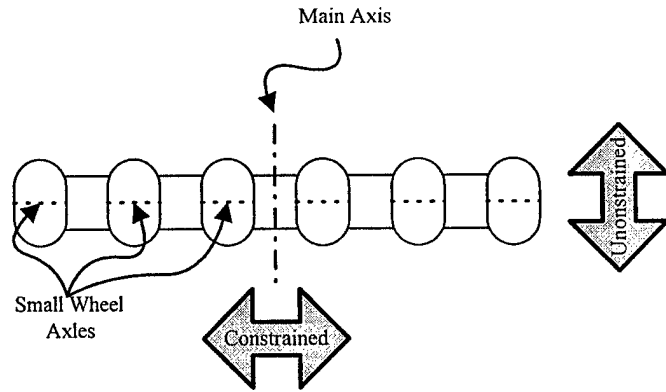
### Front View

The large wheel rotates about the main axis, which is perpendicular to the page. The motion of wheel along the horizontal direction, relative to the page is constrained.



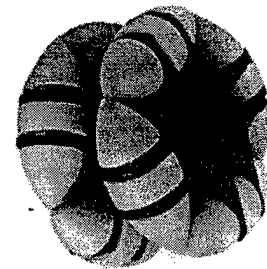
Each small wheel rotates freely about its individual axis. This allows unconstrained motion in the direction perpendicular to page.

### Top View



**Figure 40: Universal Wheel**

Figure 41 shows a commercially available multidirectional roller (Roll-Flex by ErgoTech) used as part of an assembly for material handling. The universal wheel is mounted wheel side up to allow the operator to move or rotate the item on the assembly line in any direction. This design is based on the use of four free turning barrel shaped rollers mounted in a 90 degree staggered pattern around the perimeter of a main core wheel, thus allowing for a multi-directional roller function. The open construction gives the Roll-Flex rollers a long service life without requirements for maintenance or lubrication, while relieving the user of problems caused by ingress of dirt, water etc. The multidirectional roller function is optimized in a paired duplex configuration, with the two wheels staggered by 45 degrees to minimize the bounce associated with the transition between two of the barrel rollers. The largest of these rollers has a main wheel diameter of 4.72 inches and can carry a load of 550 lb. in the duplex configuration.

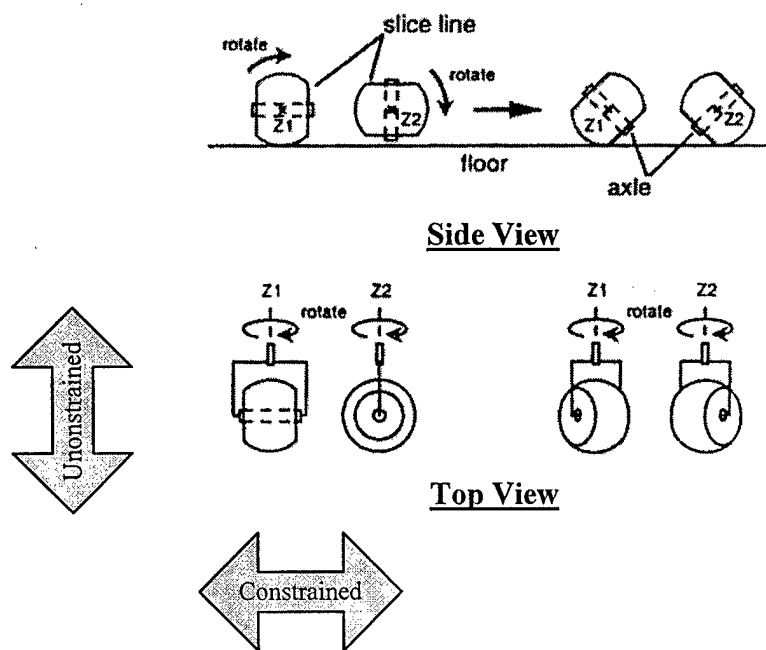


**Figure 41:  
Commercially  
Available Universal  
Wheel**

#### *4. Orthogonal-Wheels*

The orthogonal wheel assembly consists of two spherical tires which have been sliced to allow mounting surfaces for an internal axle. Each spherical tire is freewheeling about its internal axle, much like the small tires of the universal wheel. The internal axles of the two spherical wheels are mounted at right angles to ensure that one of the spherical wheels will be in contact with the

ground at all times. These internal axles are connected to the drive motor which rotates them in a direction orthogonal to both internal axes. This motion creates the constrained direction. The freewheeling internal axles always allow motion perpendicular to the constrained direction, as shown in Figure 42.



**Figure 42: Orthogonal-Wheel Concept**

The only system requirements for building an omnidirectional platform with orthogonal wheel assemblies is that the constrained rotation axis of the wheels are parallel, the sphere's center is at a constant ground offset, and that a point on one of the spheres maintains ground contact. A simple omnidirectional platform can be constructed with three such assemblies. Figure 43 shows one such platform demonstrating omnidirectionality by performing cursive handwriting.



**Figure 43: Orthogonal Wheel Platform**

## Appendix C: Scale Prototype Motor Selection

### Design Parameters

#### Dimensions

Wheel Diameter	8 in
Length	36 in
Width	24 in
Height	9 in
Ground Clearance	3 in

#### Weight Calcs

	Wt(lb)	Qty
Wheel	2	4
Motor and Gearhead	2	4
Battery	3.5	2
Frame	8	1
Electronics	0.5	1

Vehicle Weight	31.50 lb
Payload	20 lb
Design Safety Factor	1.5
DriveTrain Friction	5% of weight

Speed on max slope	3 mph
	52.8 in/s

Max Speed	5 mph
	88 in/s

Ramp Incline	8 deg
Max ship roll angle	0 deg
Total Max Angle	8 deg

Gross Vehicle Weight	51.50 lb
Weight per wheel	206 oz
	12.875 lb

Total Drivetrain Friction	2.58 lb
Total Drive Force for max angle	9.74 lb

Conversion Factor	
Nm -> oz-in	141.619

### Motor Parameters

Vendor	Pittman
Motor Model	GM9236
Brush Type	Brush
Gearhead Model	

Gearhead Ratio	:1	19.7
Gearhead Efficiency		73%
Torque Constant	oz-in/A	6.49
Friction Torque	oz-in	0.8
Motor Voltage	volts	24

Gearbox Rated Torque	oz-in	500
Stall Torque	oz-in	61.8
No-Load Speed	rpm	4916

Rated Torque?	214%
Stall Torque?	362%
Speed at Max Slope?	143%
Max Speed?	109%

Stall Torque OK?	TRUE
Speed at Max Slope OK?	TRUE
Max Speed OK?	TRUE

#### Max Slope Condition

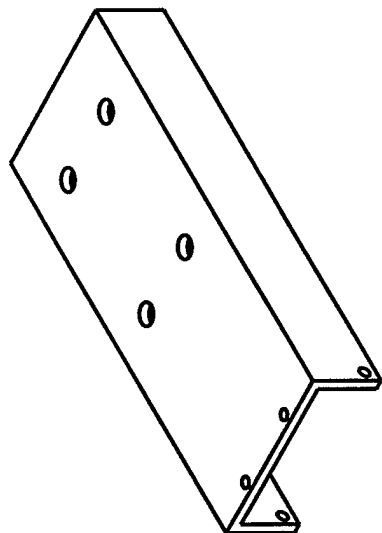
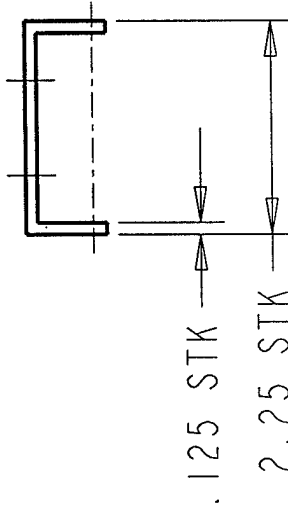
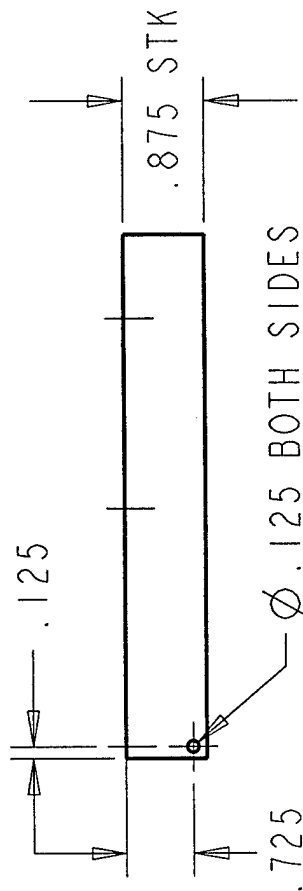
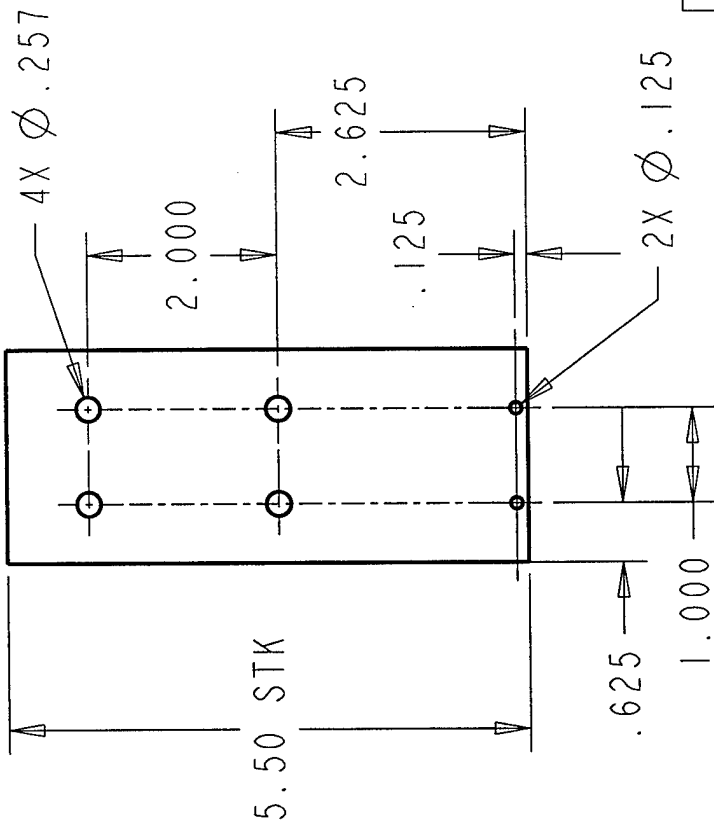
Wheel torque	in-lb	14.61
	oz-in	233.82
Motor torque	in-lb	1.07
	oz-in	17.06
Wheel speed - Design	rpm	126
Motor speed - Design	rpm	2483
Motor speed - actual	rpm	3559
Wheel speed - actual	mph	4.30
Mechanical Power	watt	31.68
Current	amps	2.63
Electrical Power at motor	watt	63.08
Total Efficiency		50%

#### Max Speed Condition

Wheel torque	in-lb	3.86
	oz-in	61.80
Motor torque	in-lb	0.32
	oz-in	5.10
Wheel speed - Design	rpm	210
Motor speed - Design	rpm	4139
Motor speed - actual	rpm	4511
Wheel speed - actual	mph	5.45
Mechanical Power	watt	10.61
Current	amps	0.79
Electrical Power at motor	watt	18.85
Total Efficiency		56%

## Appendix D: Scale Prototype Bill Of Materials

Qty	Part Number	Description	Cost	Vendor
<b>Purchase Parts</b>				
8	2015	End Cap For 1010 x .125 Thick - Fasteners Included	\$ 1.00	8020 Inc
3	2820	Black Economy T-Slot Cover 10 Series	\$ 1.75	8020 Inc
16	3280	1/4-20 Double Economy T-Nut For 1010	\$ 0.65	8020 Inc
6	3342	1/4-20 X 1/2" Flanged BHSCS	\$ 0.28	8020 Inc
36	3356	1/4-20 X 1/2" Flanged BHSCS, Double Economy T-Nut	\$ 0.90	8020 Inc
6	3376	1/4-20 Drop In T-Nut For 10 Series	\$ 1.60	8020 Inc
12	3382	1/4-20 Economy T-Nut for 10 Series	\$ 0.20	8020 Inc
6	3390	1/4-20 X 3/8" Flanged BHSCS	\$ 0.37	8020 Inc
8	4108	10 Series 1/8" Inside Corner Bracket	\$ 2.60	8020 Inc
16	4113	10 Series 4 Hole Inside Corner Bracket	\$ 3.85	8020 Inc
6	4141	10 Series 4 Hole Tee Joining Plate	\$ 5.50	8020 Inc
4	4183	10 Series 90 Deg Living Nub	\$ 17.25	8020 Inc
4	4250	10 Series 3 Hole Slotted Corner Bracket	\$ 4.25	8020 Inc
5	1010-24	1010 Extrusion - Cut to length (7005) 24 inches	\$ 6.89	8020 Inc
4	1010-9	1010 Extrusion - Cut to length (7005) 9 inches	\$ 3.74	8020 Inc
1	DX-380-2MF-SIB-AG	DX-380 marine sensor with full bridge 2 axis design	\$ 350.00	Bokam Engineering
1	P-200	post and knob for DX-380	\$ 20.00	Bokam Engineering
4	6202105	Trantorque Mini 1/4" shaft	\$ 24.13	Fener Drives
128	6389K627	Nylon Flange Bearing, 1/4" ID, 3/8 lg	\$ 0.21	McMaster
240	90272A106	Pan Head Screw 4-40 1/4" lg	\$ 0.01	McMaster
8	90276A537	Round Head Screw 1/4-20 1/2" lg	\$ 0.02	McMaster
4	91259A106	Shoulder Bolt 1/4" dia x 3" lg	\$ 5.56	McMaster
64	91259A544	Shoulder Bolt 1/4" dia x 1.25" lg	\$ 0.77	McMaster
4	91831A029	Nylon Insert Nut 1/4-20	\$ 0.07	McMaster
8	9657K123	Spring 2" lg, 3/8" OD, .047" dia	\$ 0.33	McMaster
4	GM9236S021	Brush Gearmotor, 19.7:1 ratio, 24 volt, 500 CPR encoder	\$ 135.55	Pittmann
2		Battery 12 V, 4.0 Ah		
<b>Materials</b>				
4	Alum Channel, Sharp Corner	2.25" wide, 7/8" tall, 1/8" thick x 5.50" long	\$ 4.17	Schupan
4	Aluminum Bar	6061 - 1/4" thick, 2" wide, cut to length: 1.80" +/- .005"	\$ 4.74	Schupan
32	Aluminum Architectural Angl	6063 - 1.5" x 1.5" x 1/8" cut to length: 1.00" +/- .005"	\$ 0.65	Schupan
<b>Machining</b>				
4	325-9001	Motor Mount	\$ 14.00	Pinnacle Engineering Co
4	325-9002	Faceplate	\$ 46.00	Pinnacle Engineering Co
32	325-9003	Idler Mount	\$ 5.50	Pinnacle Engineering Co
32	325-9004	Axle Block (includes maerial cost)	\$ 6.60	Kent Pruss
<b>FDM</b>				
64		Idler	\$ 6.84	FDM
4		Hub	\$ 21.23	FDM



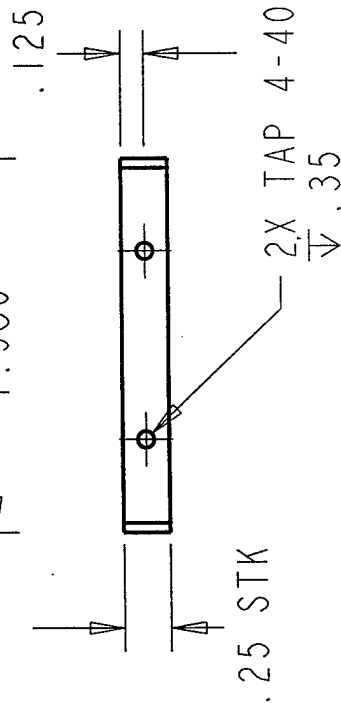
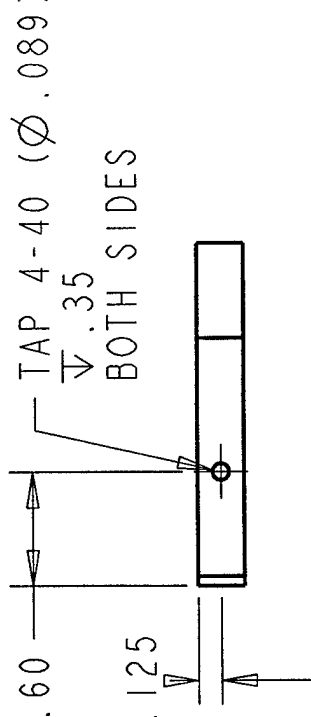
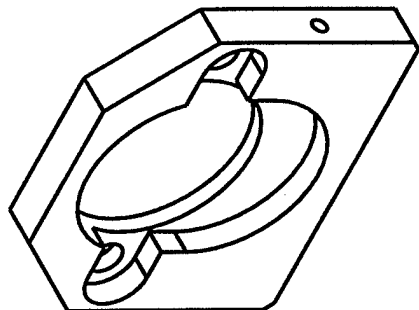
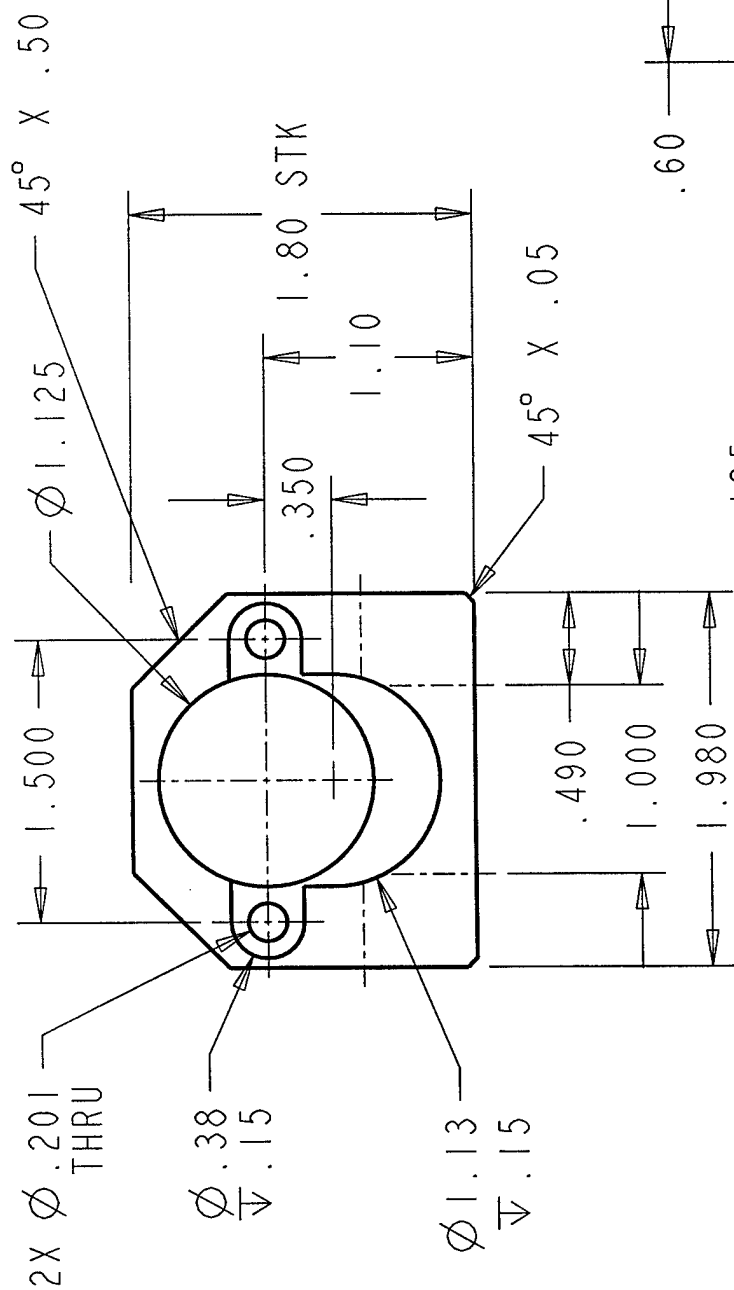
**Cybernet Systems Corporation**  
Ann Arbor, MI

Part Name: Motor Mount			
Material: Alum 6063		Finish:	
File: MOTOR_MOUNT_U-225		Type: PART	
Drawn: T. Cussen	Checked:	Approved:	
Dwg No: 325-9001		Rev: 1	
Date: 04-Aug-99	Sheet: 1 of 1	Scale: 0.50	Size: A

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- \* Diameters on a common center line concentric within 0.005 T.I.R.
- \* Squareness and parallelism of surfaces 0.002 per inch to a max. of 0.012 for single surface
- \* All machined surface finish 64 RMS Max

- \* All dimensions are in inches
- \* Tols: X.X ±0.1  
X.XX ±0.01  
X.XXX ±0.003  
X.XXX ±0.005  
X.XX ±0.50  
X.XX ±0.50
- \* Angular tols: X.X ±0.5  
X.XX ±0.50
- \* Fillet radii - 0.015 max
- \* Remove all burrs and break all sharp edges to 0.015 max



**Cybernet Systems Corporation**  
Ann Arbor, MI

Ann Arbor, MI

Part Name: Faceplate

Material: Alum 6061

File: MOTOR_FACEPLATE-225	Type: PART
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Drawn:	Checked:	Approved:
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Dwg No: 325-9002

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Date: 04-Aug-99	Sheet: 1 of 1
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Scale: 1.00  
Size: A

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- # Diameters on a common center line concentric within 0.005 T.I.R.
- # Squareness and parallelism of surfaces 0.002 per inch to a max. of 0.012 for single surface
- # All machined surface finish 64 RMS Max

# All dimensions are in inches

# Tols:

X.XX ±0.1

X.XX ±0.01

X.XXX ±0.003

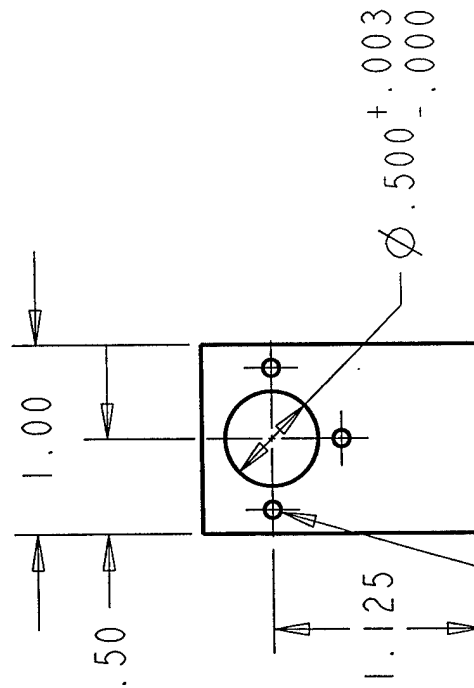
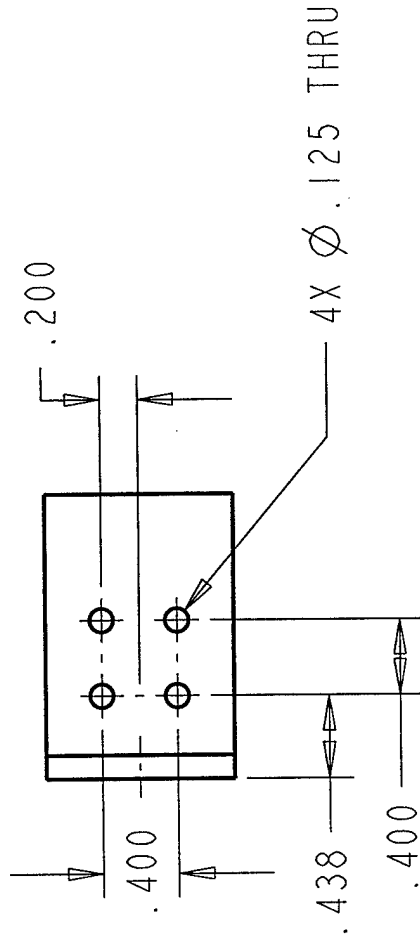
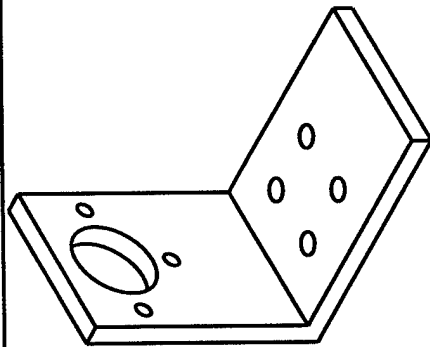
# Angular tols: X.X ±0.5

X.XX ±0.50

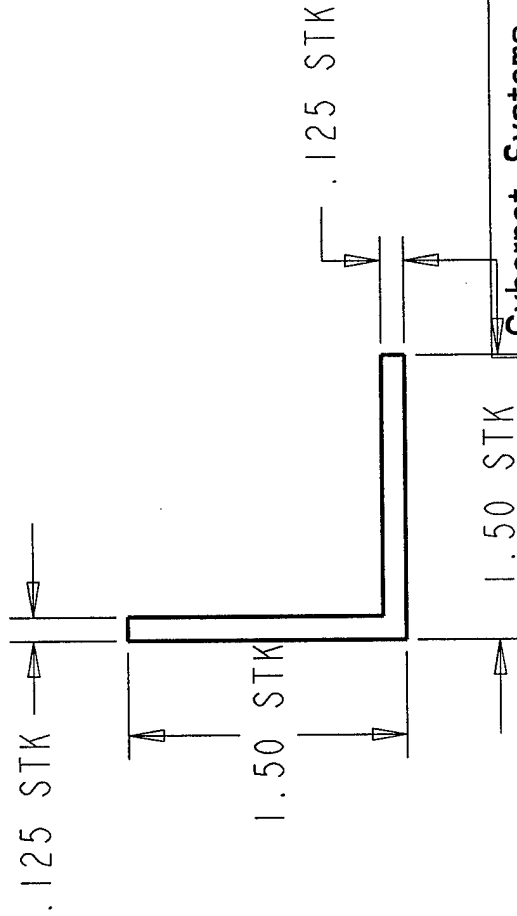
# Fillet radii - 0.015 max

# Remove all burrs and break

all sharp edges to 0.015 max



3X TAP 4-40 (Ø.089)  
ON .750 B.C.



Cybernet Systems Corporation  
Ann Arbor, MI

Part Name: Idler Mount

Material: Alum 6063	Finish:
File: IDLER-BRACKET	Type: PART
Drawn: T. Cussen	Checked:
Dwg No: 325-9003	Rev: 1
Date: 06-Aug-99	Sheet: 1 of 1
Scale: 1.00	Size: A

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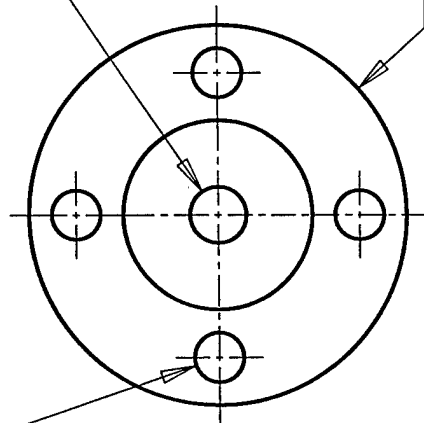
- \* Diameters on a common center line concentric within 0.005 T.I.R.
- \* Squareness and parallelism of surfaces 0.002 per inch to a max. of 0.012 for single surface
- \* All machined surface finish 64 RMS Max

- \* All dimensions are in inches
- \* Tols: X.X ±0.1  
X.XX ±0.01  
X.XXX ±0.003  
X.XXX ±0.005  
X.XX ±0.5
- \* Angular tols: X.X ±0.5
- \* Fillet radii - 0.015 max
- \* Remove all burrs and break all sharp edges to 0.015 max

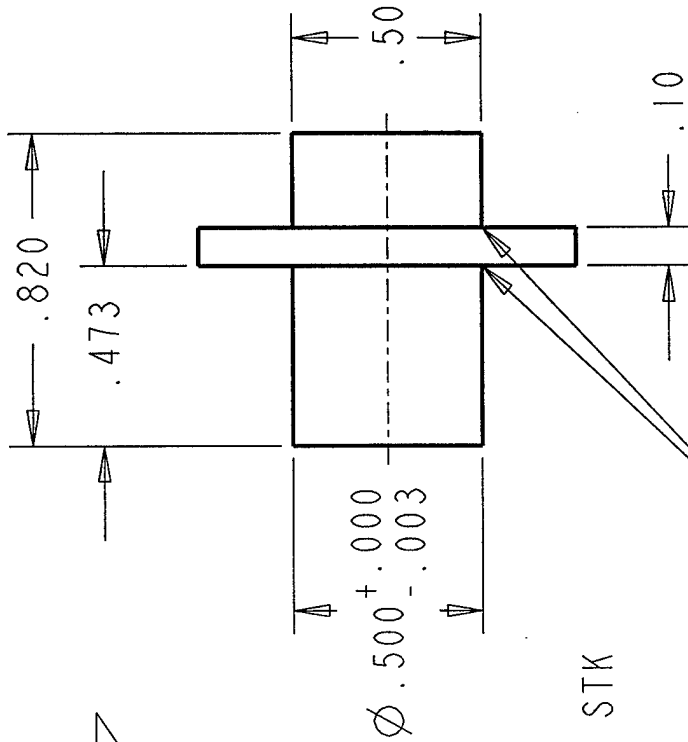


4X  $\phi .13$   
EQ SP ON .75 B.C.

TAP 10-24 ( $\phi .149$ ) THRU



$\phi 1.00$  STK



If necessary, add relief grooves  
less than .06 wide.

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Ann Arbor, MI

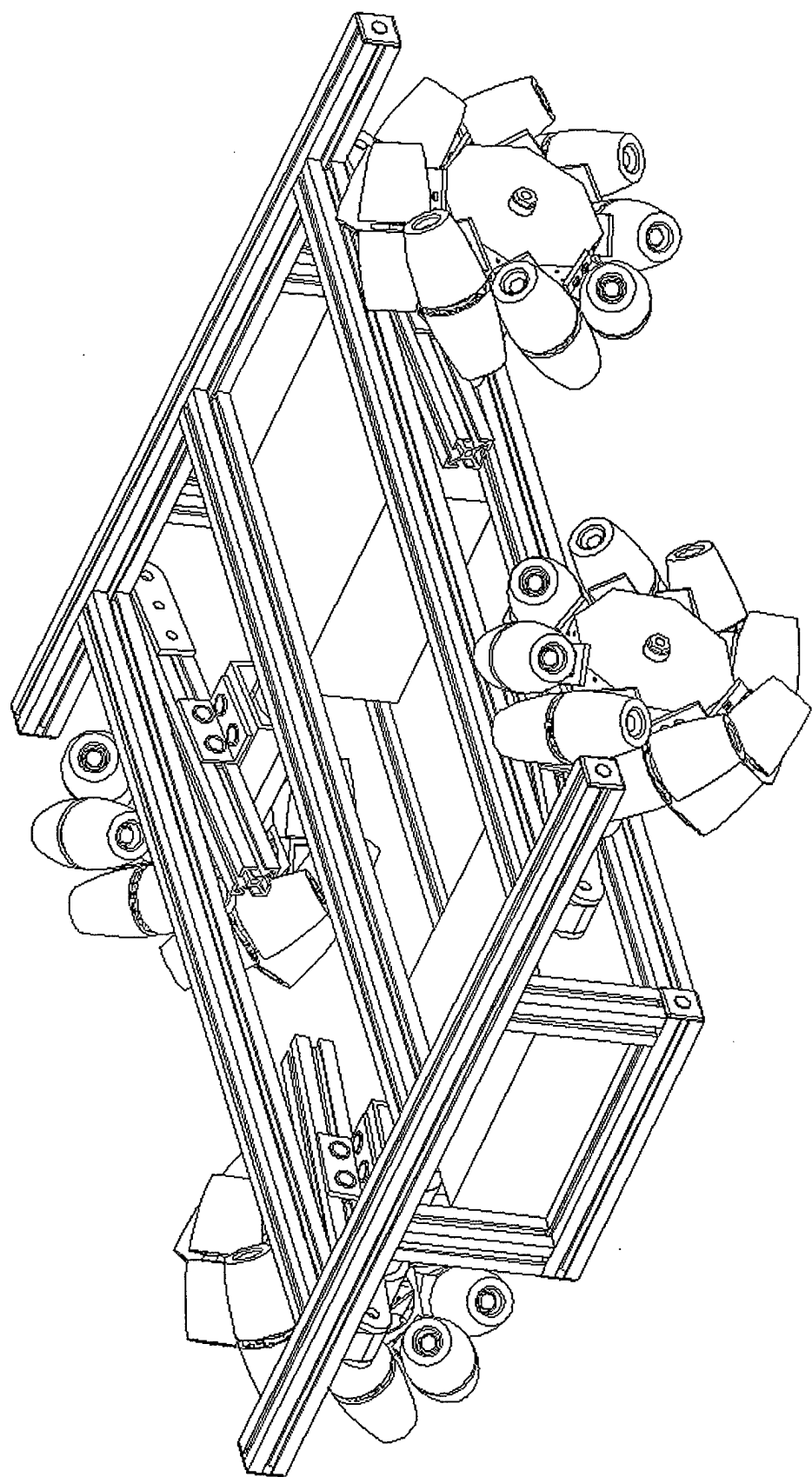
Part Name: Axle Block

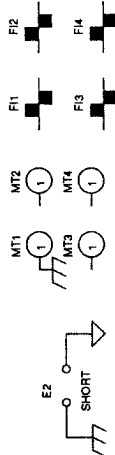
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File: AXLE-BLOCK	Type: PART
Drawn: T. Cussen	Checked:
Dwg No: 325-9004	Approved:
Date: 06-Aug-99	Sheet: 1 of 1
Scale: 2.00	Size: A

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- \* Diameters on a common center line concentric within 0.005 T.I.R.
- \* Squariness and parallelism of surfaces 0.002 per inch to a max. of 0.012 for single surface
- \* All machined surface finish 64 RMS Max

- \* All dimensions are in inches
- \* Tols: X.X  $\pm 0.1$   
X.XX  $\pm 0.01$   
X.XXX  $\pm 0.003$   
X.XXX  $\pm 0.5$   
X.XX  $\pm 0.50$
- \* Fillet radii - 0.015 max
- \* Remove all burrs and break all sharp edges to 0.015 max





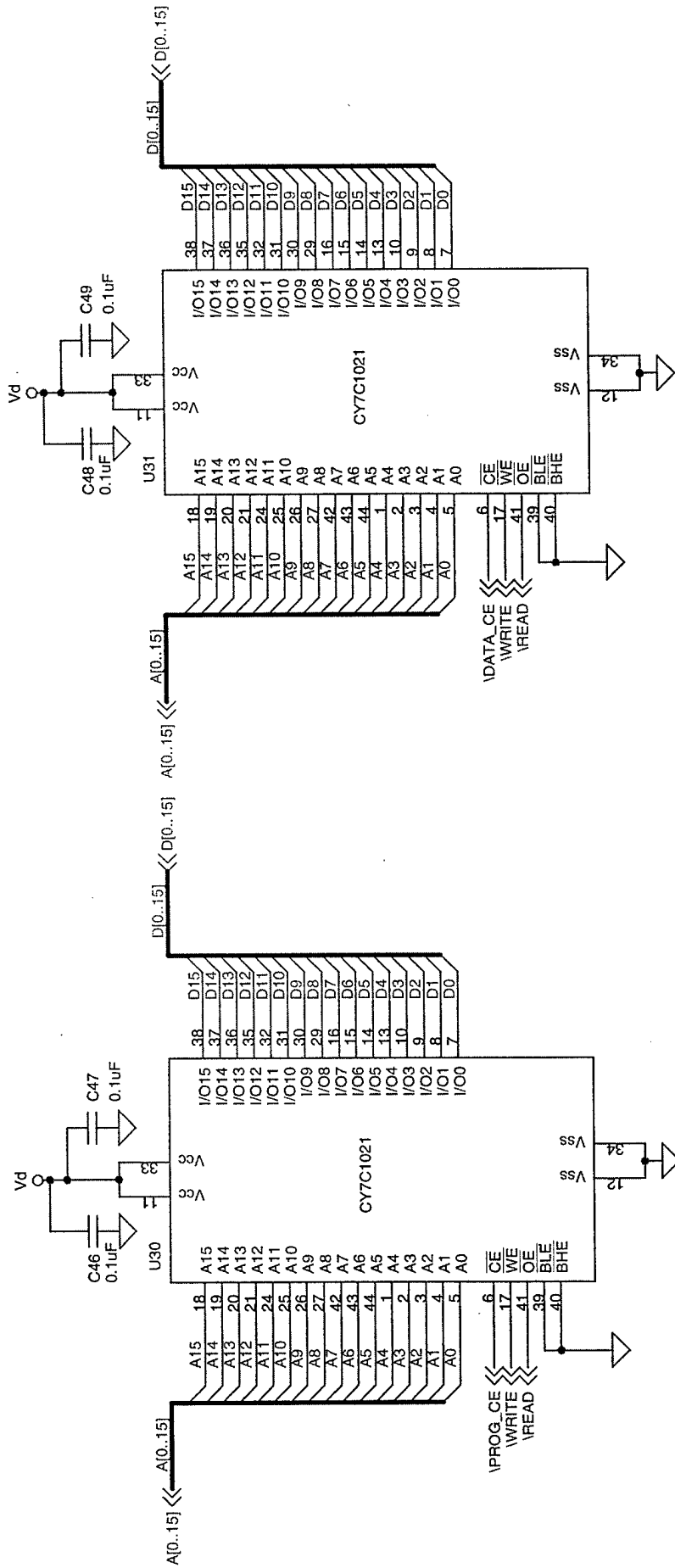
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**Cybernet Systems Corporation**  
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Size	Document Number
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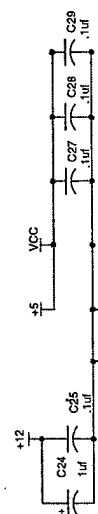
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Date:	Monday, September 27, 1999	Sheet 1 of 11	

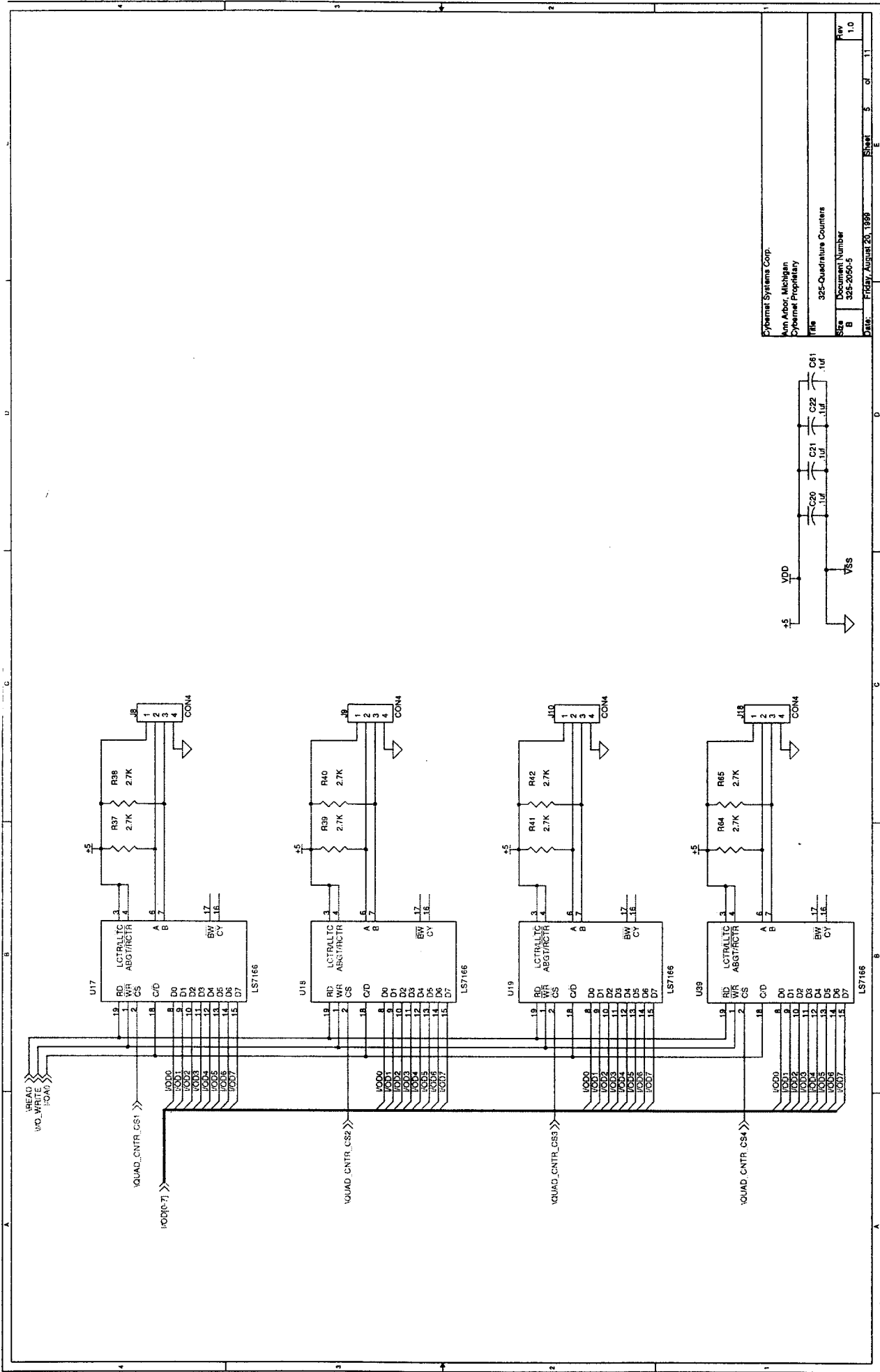


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Cybernet Systems Corporation		Ann Arbor, Michigan	
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Size	Document Number	Rev	
A	325-2050-1	1.0	
Date:	Friday, August 20, 1999	Sheet	2 of 11



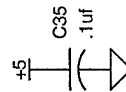




Cydacal Systems Corp.		
Ann Arbor, Michigan		
Dynamal Proprietary		
Title 325-Quadrature Counters		
Size B	Document Number	Rev
325-2050-5		1.0
Date	Friday, August 20, 1989	Sheet 5 of 11







Ann Arbor, Michigan  
Cybernet Proprietary

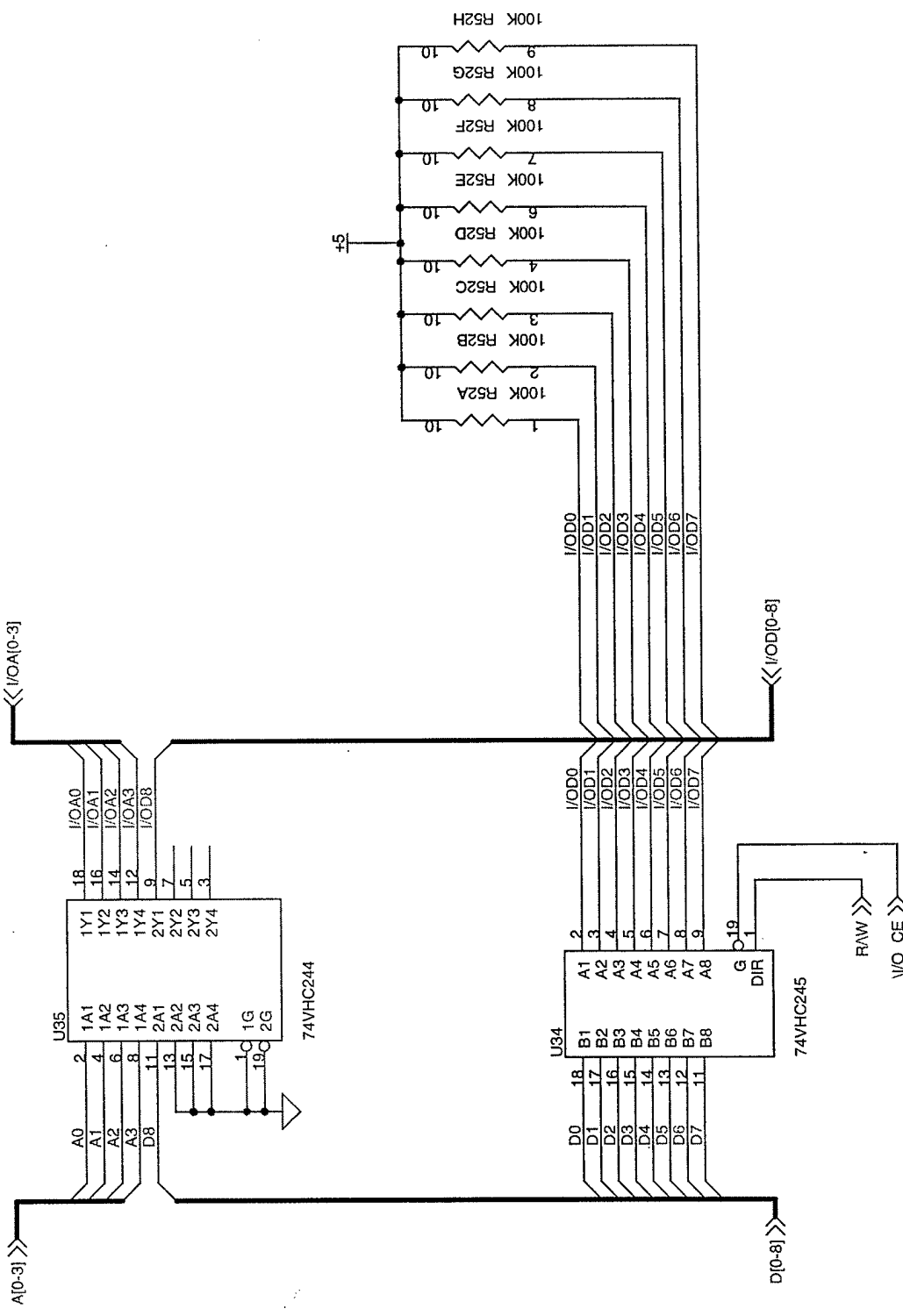
## RS-232 Drivers

Rev

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**D**



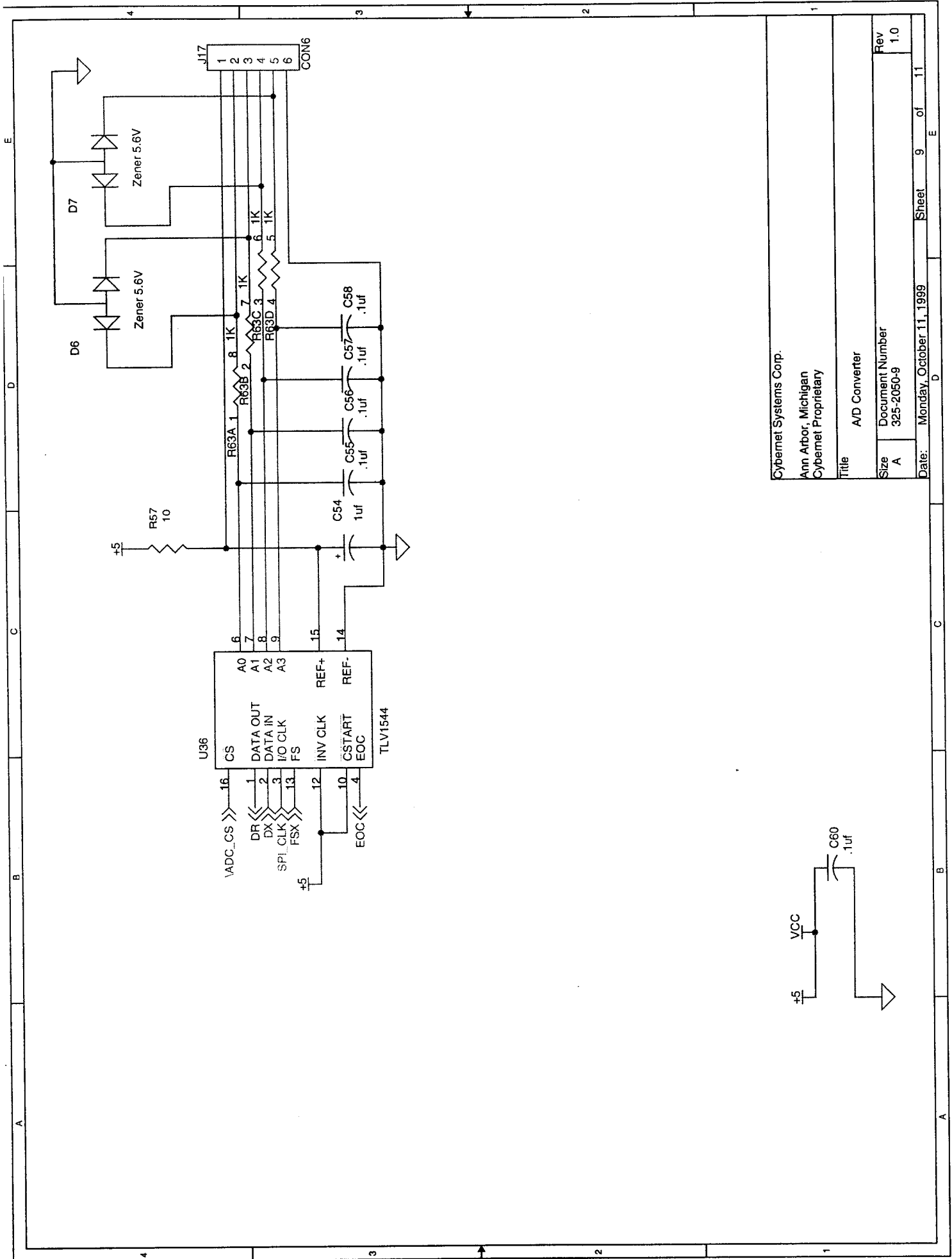
Cybernet Systems Corp.

Ann Arbor, Michigan  
Cybernet Proprietary

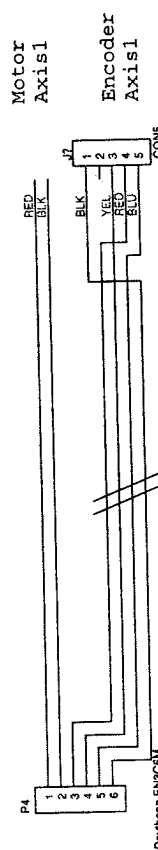
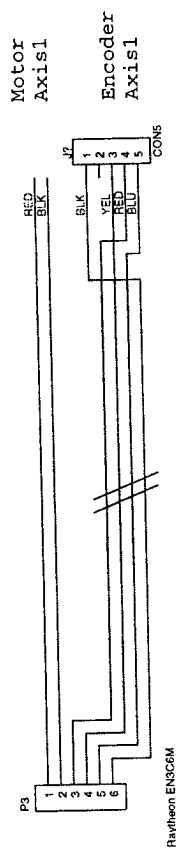
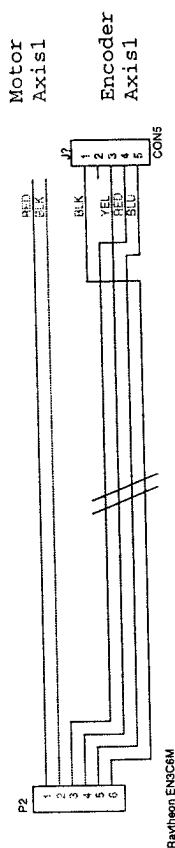
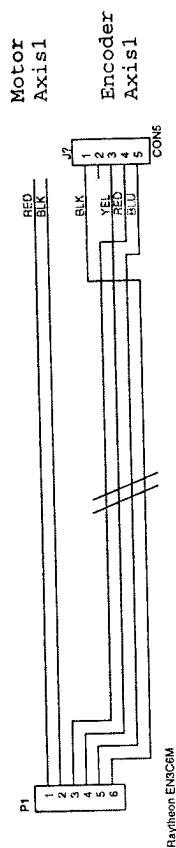
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Size	Document Number	Rev
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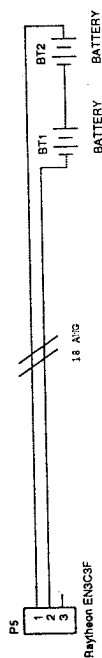
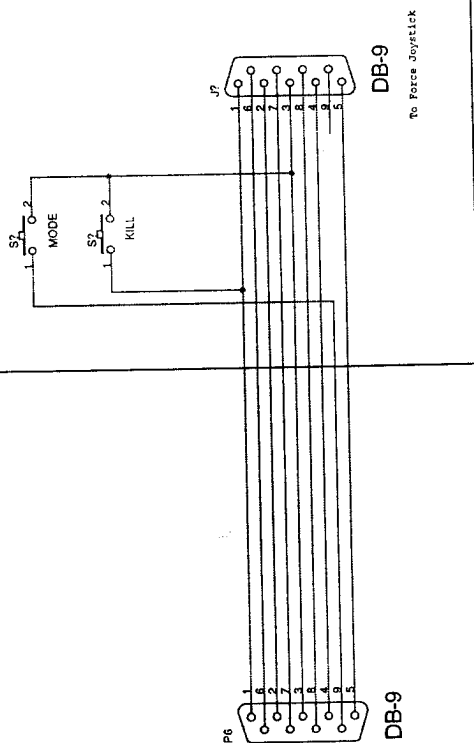
Date: Friday, August 20, 1999 Sheet 8 of 11



Cybernet Systems Corp.	
Ann Arbor, Michigan	
Cybernet Proprietary	
Title A/D Converter	
Size A	Document Number 325-2050-9
Rev 1.0	
Date: Monday, October 11, 1999	Sheet 9 of 11



Control Box



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Aur Arbor, Michigan

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Title External Wiring

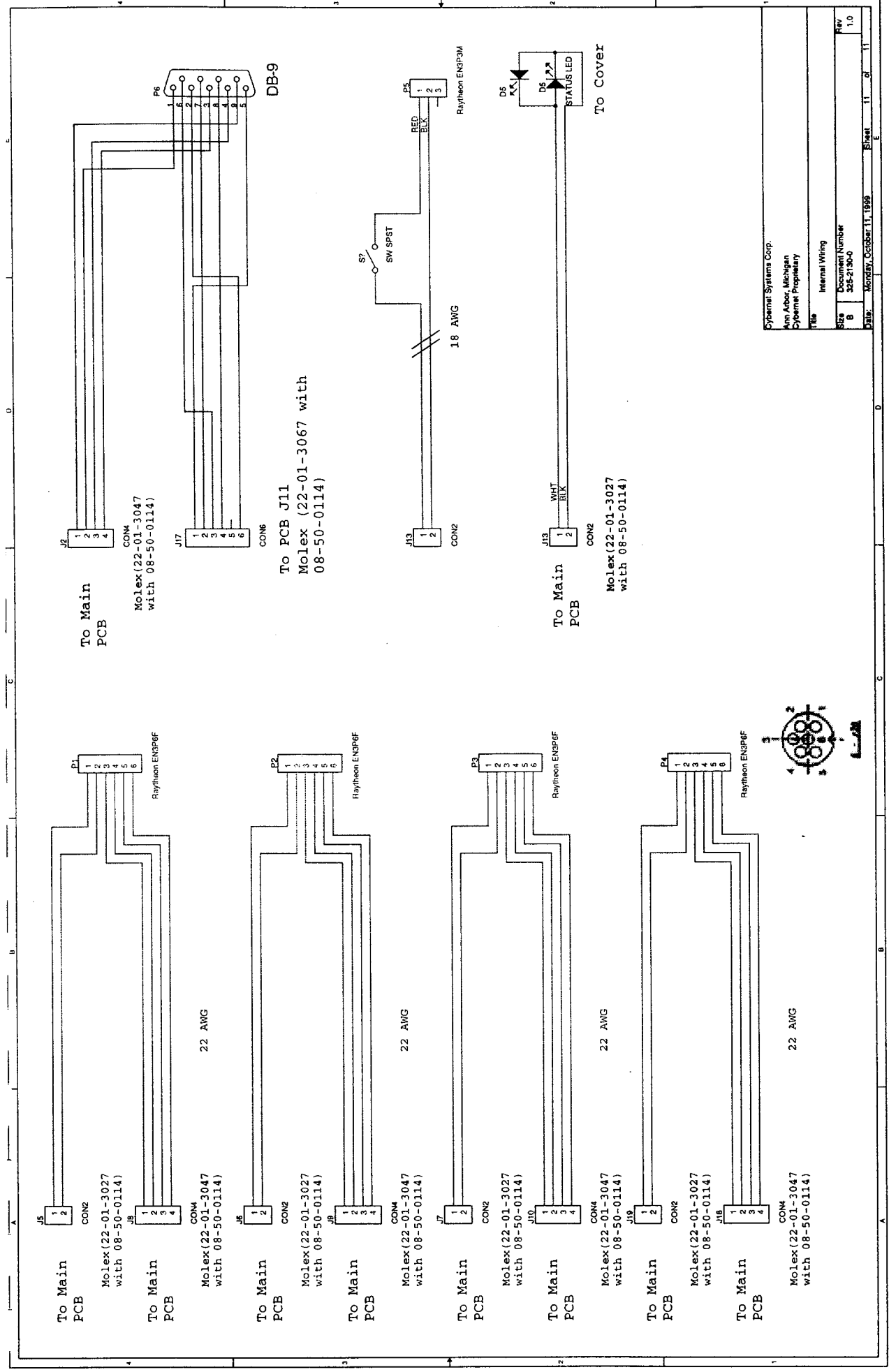
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Document Number 325-2120-0 External Wiring

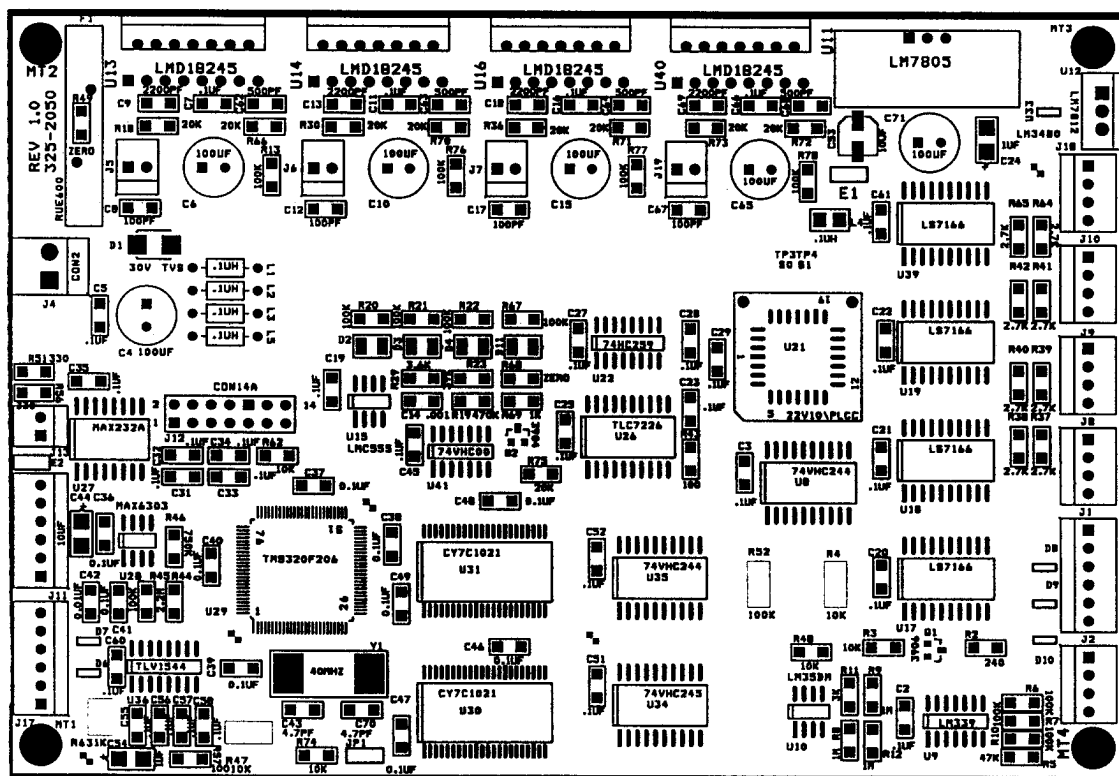
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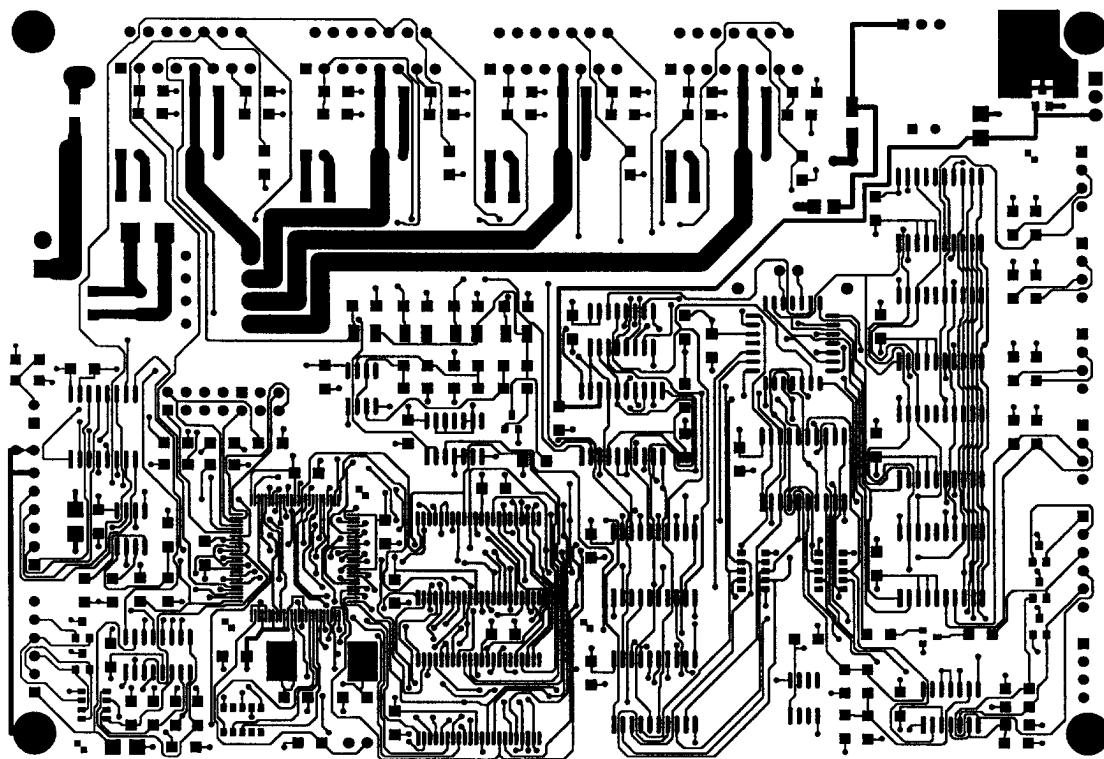
Sheet 1 of 1

Rev 1.0



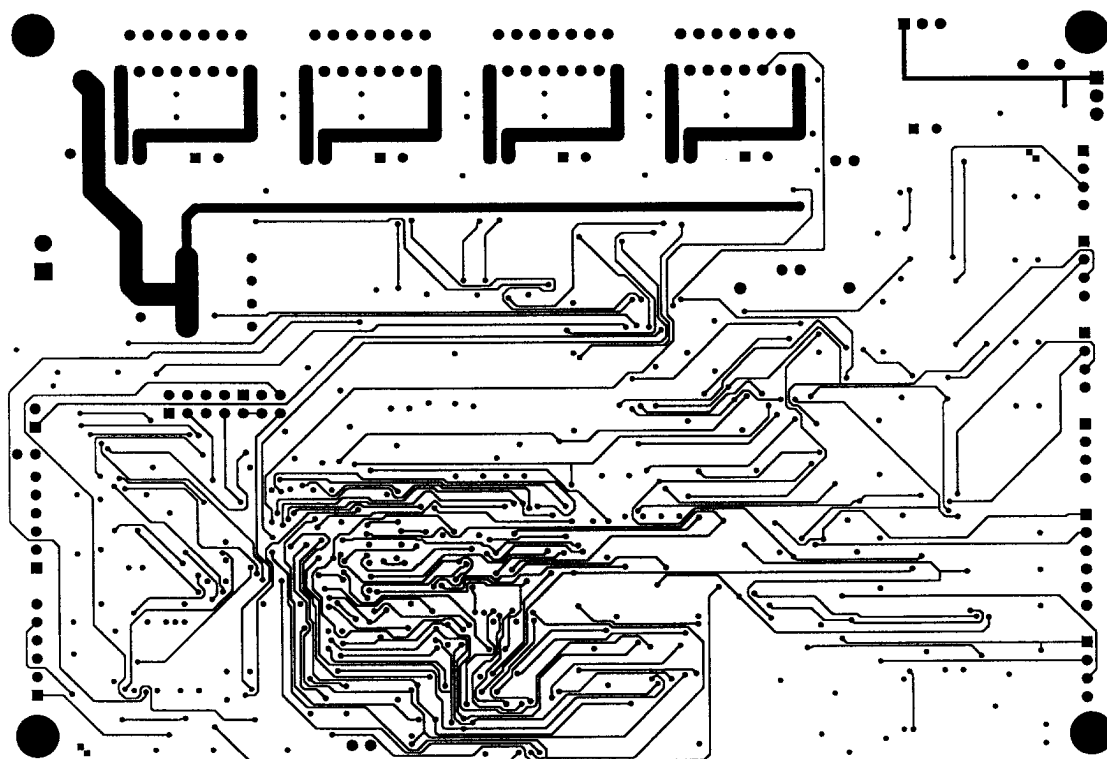
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Ann Arbor, Michigan			
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Size	Document Number	Rev	
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Date:	Monday, October 11, 1999	Sheet	11 of 11





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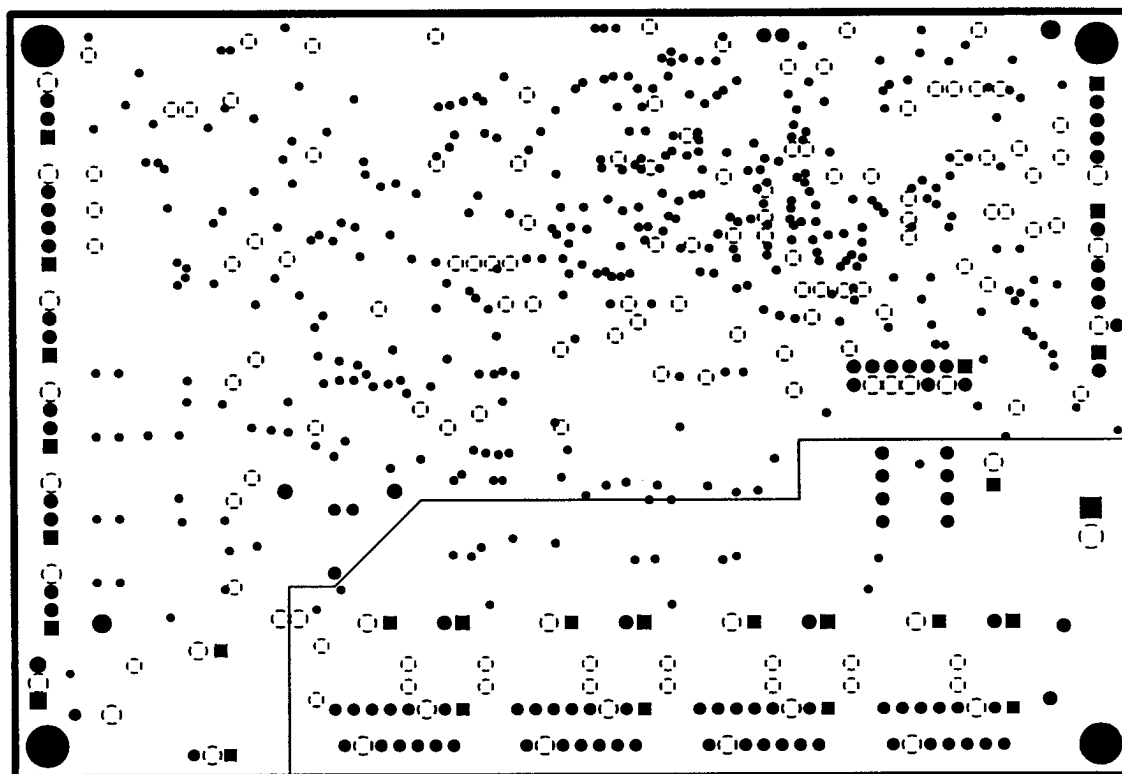
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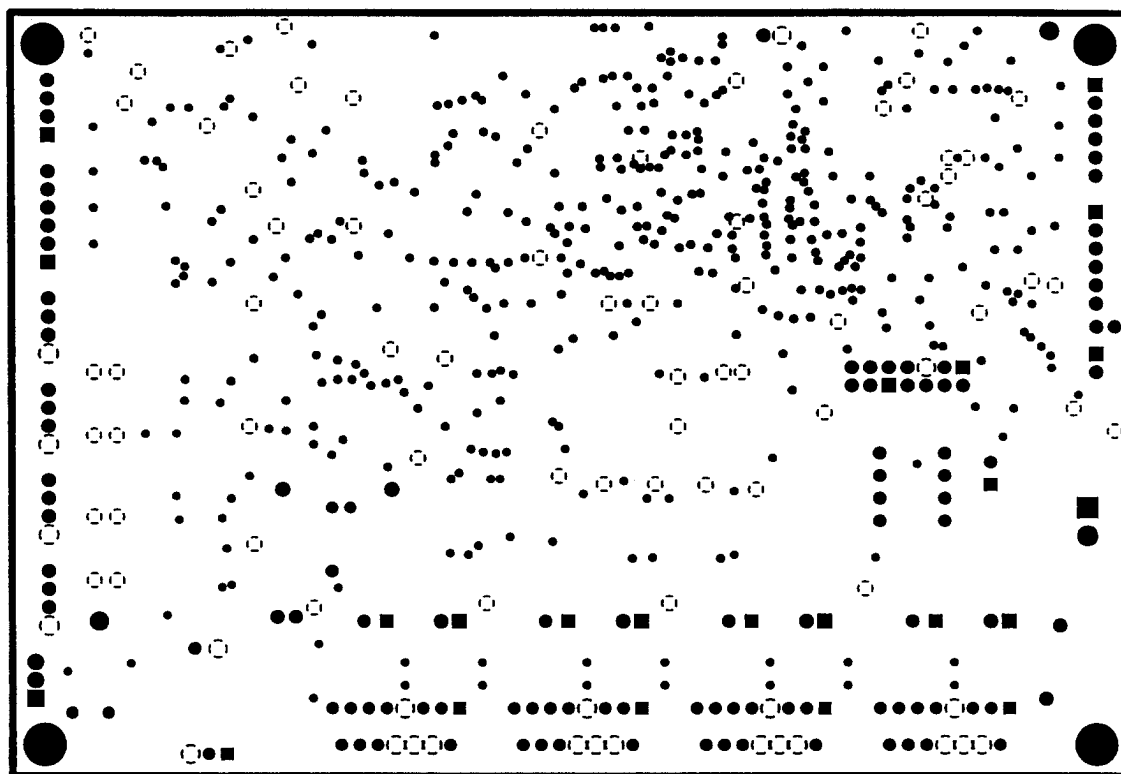


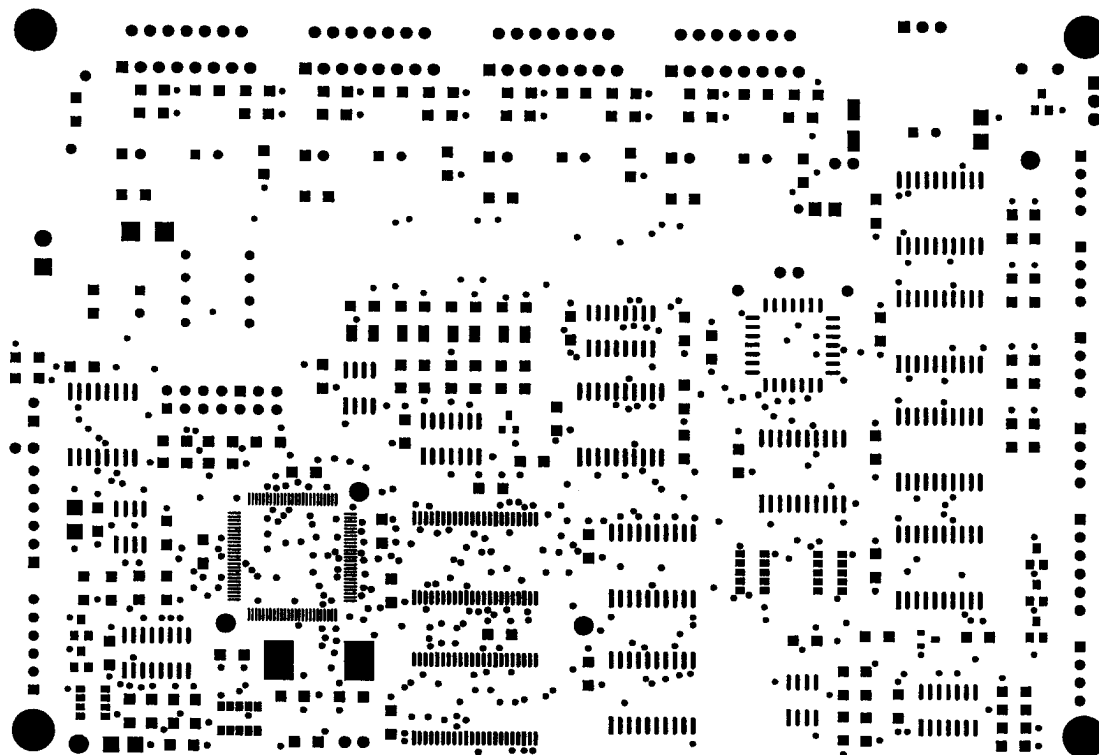
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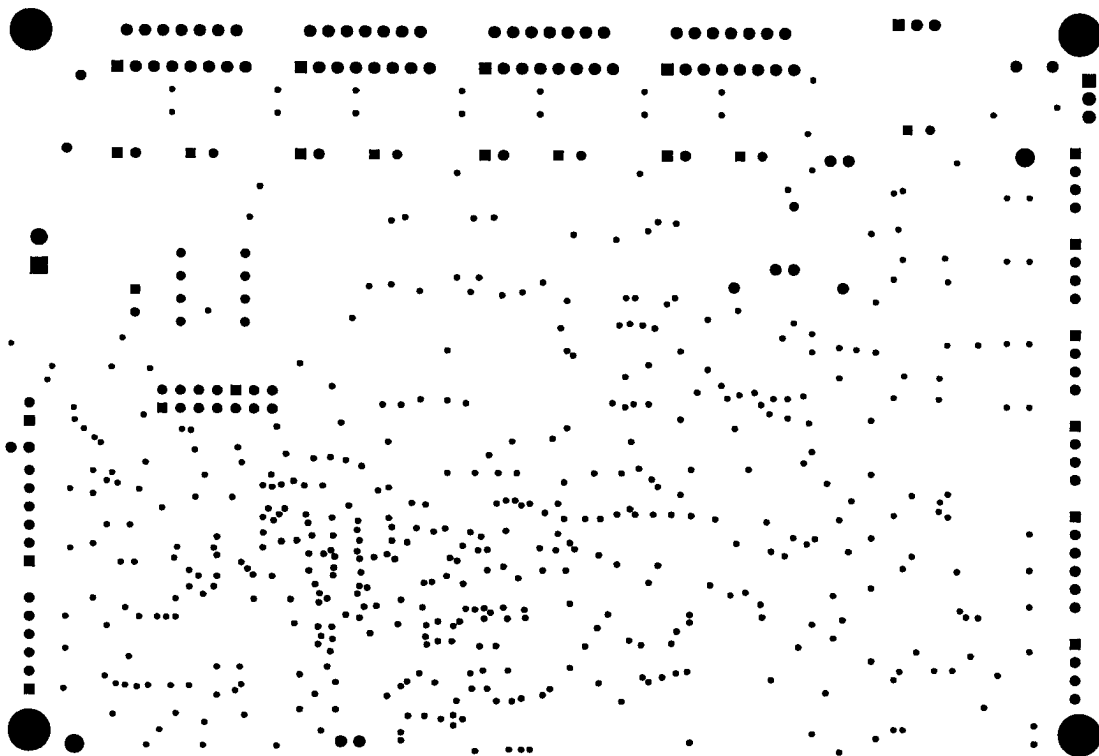








SMTOP  
CYBERNET PROPRIETARY



SMBOTTOM

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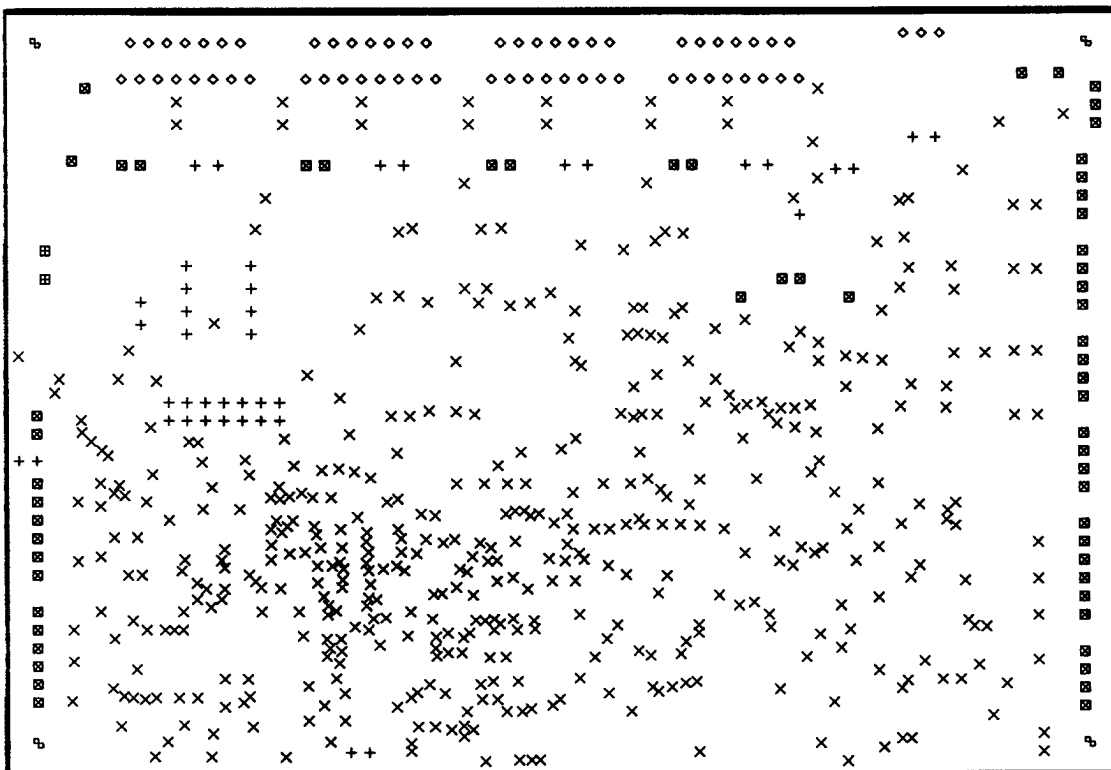
TP3TP4

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**SSTOP**





CYBERNET PROPRIETARY

BOARD SIZE: 0,0 to 4.200,6.100  
 BOARD: .062 (STD)  
 COPPER: 2 oz. (STD)  
 4 LAYER PLATED THRU  
 MIN. TRACE WIDTH: 8MIL  
 SOLDER MASK: 2 SIDES  
 LEGEND: 1 SIDE  
 GOLD: NONE

HOLE LEGEND				
SYM	DIAM	TOL	QTY	NOTE
x	0.018		478	
+	0.034		41	
o	0.038		63	
■	0.042		59	
■	0.070		2	
■	0.156		4	
TOTAL			647	